SYSTEMATIC APPROACH TO DEVELOP A STRINGER COUPLING CONCEPT

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Aeronautical Engineering

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TIIVISTELMÄ

Tampereen ammattikorkeakoulu
Kone- ja tuotantotekniikan koulutusohjelma
Lentokonetekniikkan suuntautumisvaihtoehto

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Systemaattinen lähestyminen lentokoneen pituusjäykisteiden liitoskappale konseptien kehitykseen

Opinnäytetyö 81 sivua, joista liitteitä 2 sivua
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Pituusjäykisteen vaihdos on tarkoitus tehdä Airbus A350 XWB-1000 osan 16 – 18 pohjakuoressa, mutta tämä tarkoittaa sitä, että konseptiliitoskappale tarvitaan kahden pituusjäyskisteen yhdistämiseen. Konseptin kehityksessä tarvitsee ottaa monia asioita huomioon, jotta kytkentä voidaan suorittaa systemaattisesti. Tästä syystä kehitys suoritettiin VDI 2221 standardin avulla.

Kahden pituusjäykisteen muutoksen paikka määritettiin sekä kahden pituusjäykisteen linjauksen poikkeama asetettiin konseptin kehitysvaiheessa, jotta konsepti pystyttiin määrittämään. Kytkimen tarkoitus on luoda erittäin paikallinen jäykistys siihen kohtaan, jossa pituusjäykisteiden muutos tapahtuu. Konsepteja kehitettiin monia, mutta kolme konseptia mallinnettiin ja lujuuslaskettiin käsin. Kaksi konseptia lujuuslaskettiin ja optimoitiin yksityiskohtaisen elementti-menetelmän avulla. Lujuuslaskennassa käytettiin Airbus työkaluja. Ainoastaan yksi kuormitustapaus on otettu huomioon laskennoissa koska laskennat ovat erittäin aikaa kuluttavaa.

Kehitetyt konseptit täyttävät niille asetetut määreet ja painonlisäys koneeseen on pieni. Konsepteja tarvitsee kehittää ja analysoida lisää ennen kuin niitä voidaan käyttää lentokoneessa, koska lentokone määräykset ja säädökset ovat erittäin monimutkaisia. Tutkitut konseptit ovat erittäin hyvä pohja tuleville tutkimuksille ja kehitys-projekteille, jotta pituusjäykiste vaihdos voidaan suorittaa Airbus A350XWB-1000 koneessa.

Asiasanat: kehitys, VDI 2221, pituusjäykiste vaihdos, FEM

ABSTRACT

Tampereen ammattikorkeakoulu
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Systematic Approach to Develop a Stringers Coupling Concept

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A stringer trade was to be done in Airbus A350 XWB-1000 in the lower shell of section 16 – 18 but the trade means that there has to be a connection part or a coupling. To develop a coupling concept many aspects had to be taken into consideration. Therefore it was necessary to develop the concept with the help of a systematic guideline. The VDI 2221 guideline was selected to be the guideline to follow because of its adaptability.

The coupling location was defined and the misalignment distance was also defined during the research phase of the development. The coupling was designed to create a very local stiffness increase to cover the stiffness loss due to the stringer change. Various coupling concept were designed up to a concept level but only three were embodied and hand calculated and only two were calculated with DFEM model and optimized. Only one load case was considered in the calculations due to the time limitations in the post processing phase.

The developed concepts are fulfilling their selected requirements and the weight impact to the aircraft is small. The concepts have to be researched and developed more before they can be used in the aircraft due to the complexity of the aircraft requirements and the certification processes. The researched concepts are a good base to future development for the possibility of creating the stringer trade in the A350 XWB – 1000 aircraft.

Key words: development, VDI 2221, stringer trade, FEM

TABLE OF CONTENT

LIST OF TABLES

LIST OF PICTURES

NOTATION & SYMBOLS & UNITS

TAMK	Tampere University of Applied Sciences
ECTS	15

Definition of abbreviations

Al	Aluminium
ATL	Automated tape laying
CFD	Computational fluid dynamics
CFRP	Carbon-fiber-reinforced polymer
CFRT	Carbon-fiber-reinforced thermoplastic
DFEM	Detail finite element model
DPA	Damage prone area
FEM	Finite element method
GFEM	Global finite element model
HSB	Handbuch struktur berechnung
Mg	Magnesium
MPa	Mega Pascal
N	Newton
NRC	Non reoccurring cost
PEEK	Polyether ether ketone
PPS	Polyphenylene sulfide
RF	Reserve factor
RSDP	Reference structure design principles
RTM	Resin transfer molding
Ti	Titanium
VDI	Verein Deutscher Ingenieure

List of symbols and units

h	[mm]	Panel height
A	$[mm^2]$	Cross section area of column
$A_{Cross\ section}$	$[mm^2]$	Area of a cross section
C	[-]	Effective length factor
E_c	[MPa]	Compressive modulus of elasticity
$F_{Rivet.SU}$	[N]	Fastener shear allowable
I	$[mm^4]$	Minimum moment of inertia of column cross section
L	[mm]	Length of a coupling
L_e	[mm]	Effective column length
$RF_{Comp,hand}$	[ratio]	Reserve factor for compression with hand calculation
$RF_{comp,buck,hand}$	[ratio]	Reserve factor for compression buckling with hand calculation
$d_{fastener}$	[mm]	Fastener diameter
i	$[mm^4]$	Minimum radius of gyration of column cross section
$l_{Coupling}$	[mm]	Length of the coupling
m	[kg]	Mass
n	[-]	Fastener amount
ρ	$\left[\frac{kg}{mm^3}\right]$	Material density
$\sigma_{App.Shear.River}$	[MPa]	Applied shear stress for fastener
$\sigma_{Applied}$	[MPa]	Applied stress
$\sigma_{Compression\ buckling}$	[MPa]	Initial buckling stress
$\sigma_{Compression}$	[MPa]	Compression stress

1 INTRODUCTION

The main task of the thesis is to develop coupling concepts and analyze them. The thesis is done for a company called Bertrandt which is an engineering office for many fields of engineering. Bertrandt is a subcontractor for Airbus and the thesis was done in an Airbus environment that means that Airbus tools and regulations apply to the task.

Bertrandt was the client who ordered the research that was done in this thesis. The engineering office was established in 1974 for automotive development. The company expanded first in Germany and then to Europe and then to the USA. Bertrandt currently offers a wide range of engineering services in different fields from automotive to aerospace industry. In 2012 the company’s revenue was nearly 710 million euros. Bertrandt has nearly 10 000 employees all over the world. The company has some well-known clients such as Porsche, Airbus and Rolls-Royce. The office in Hamburg is concentrating on aeronautical services for Airbus. The office is mainly divided into design, stress and cabin departments and the departments are divided into smaller work groups with different main tasks and projects. (Bertrandt 2013)

The thesis is based on other research that was made for a stringer trade in the section 16-18 lower shell of the Airbus A350XWB-1000. The research states that the stringer trade would be weight saving and cost saving solution but the coupling of the two different stringers has not been done in this kind of a conditions before and because of this the coupling concepts had to be researched. There are stringer trade concepts but a concept where the stringer type varies and the stringers centerlines are not aligned does not exist.

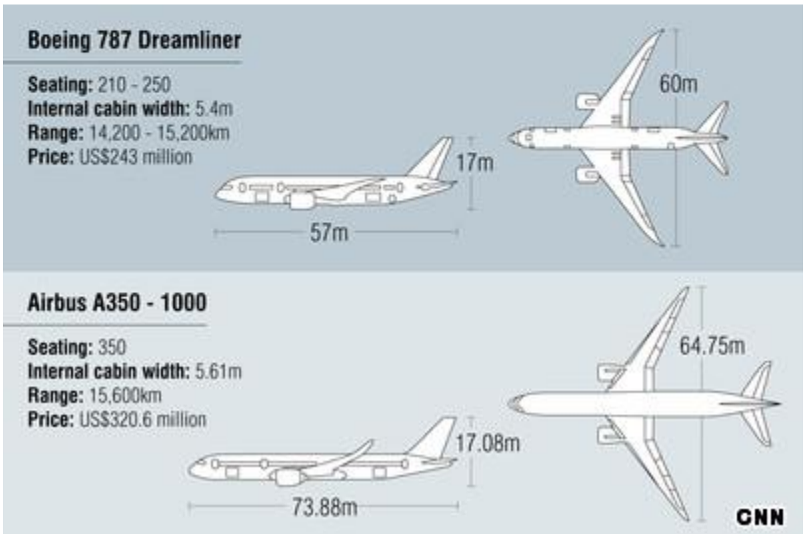
The thesis contains on two main segments and they are design development and stress analysis of the developed concepts. The design development was done with the design department and the stress analysis was done with the stress department. The development and the stress analysis were equally time-consuming. The start of both segments where difficult but when the ball got rolling results started to occur. Due to the nature of the task, some parts of the thesis are considered as classified information and therefore cannot be published.

2 GENERAL ABOUT THE AIRBUS A350

2.1 Airbus A350 XWB

The Airbus A350 family is designed for operating medium- to- long haul operations and can carry 250 to 400 persons with a three-class configuration. All of the aircrafts with in the family can reach the global range and this gives the airliner the option to use the aircrafts in their desired way. The range of the family' aircrafts are close 8 500 nautical miles and maximum take of weight is from 260 tons to 310 tons, of which about 140 to 160 tons is fuel. (Airbus, Airbus home page 2013)

The A350 is designed to the same market as Boeing's 787 Dreamliner and has nearly the same properties and the same dimensions which are shown in the Picture 1: Dreamliner in comparison to A350-1000. The use of advanced materials and latest technologies make the two aircrafts similar in many ways. In the future more of advanced materials are going to be used because of their good properties and it´s going to get less expensive during time because more companies start manufacturing with them. In June 2013 Airbus has got 678 orders from 33 airlines of the A350 although the maiden flight has not yet taken place. As a comparison Boeing has 930 orders from 58 airlines. (Boeing 2013)



Picture 1: Dreamliner in comparison to A350-1000 (Cripps 2012)

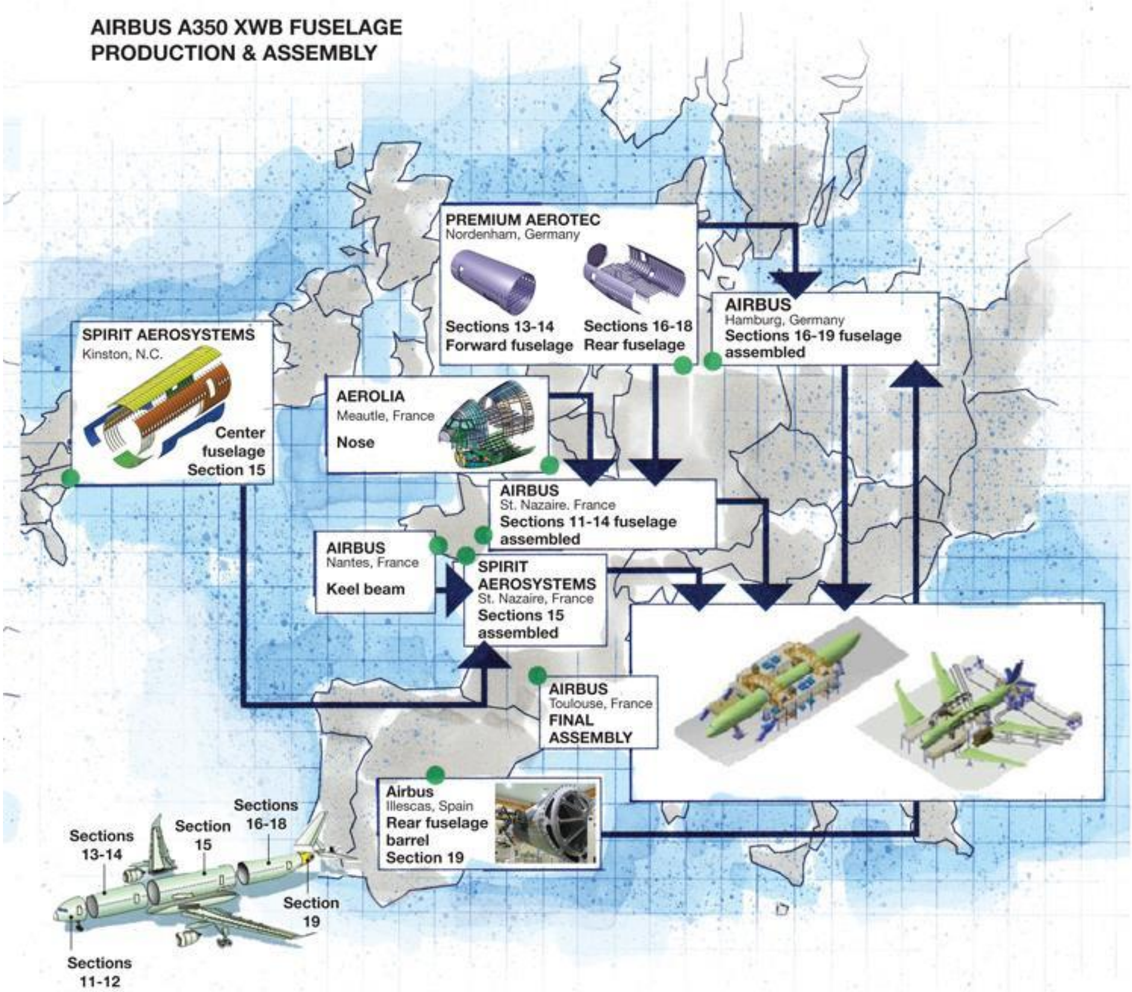
The A350 project has had some bumps on the road. In the first place the A350 was designed to have the same fuselage as the A330 but due to the potential customers' lack of satisfaction with the planned design of the fuselage Airbus decided to redesign it. For that reason the launch of the aircraft went from 2004 to 2006. The entry to service is going to happen in 2014 for the first derivative A350 XWB -900. The variations of the family are shown in the Picture 2: A350 family. (Airbus, Airbus home page 2013)

Picture 2: A350 family (Airbus, Airbus People 2013)

2.1.1 Manufacturing

Main goal in the design of the A350 is a significant reduction of operating and maintenance costs compared to the market's current leader. To reach these goals the concept had to be lighter than before. Also the aerodynamics and the power plants had to be optimized. The environment has also been taken into account when designing the A350. By fuel efficiency the CO2 emissions are lowered and also the material choices were made so that the environment was favored. The most environmental-friendly options that are possible to use have to be used. This includes for example use of water based paint and also thermal spraying is used instead of chrome-plating. (Airbus, Airbus home page 2013)

Major components of the A350 are assembled in Germany, France, Spain and the UK. Single parts and even some major components are supplied by risk share partners worldwide and the final assembly is made in France. In UK the wings are assembled in Broughton and from where they are sent to Bremen in Germany for equipping and then they are on their way to Toulouse in France. A further example of the complex logistics is the wing assembly. Upper wing skin is produced in Stade, Germany where as the lower skin is manufactured in Lilescas, Spain. The center wing box, which collects the main loads, is assembled in Nantes, France. All of these production plants have automatic tape layers and large scale autoclaves. The nose and the center fuselage are made in France and the section 19 is made in Spain and the rear section of the fuselage is assembled in Germany. The A350's engines manufacturer is Rolls Royce. The landing gears are made by two different companies that are Messier-Bugatti-Dowty who makes the main landing gear and the nose landing gears are manufactured by a company called Liebherr-Aerospace. The Picture 3: Manufacturing flow chart shows the flow chart of the production of the aircraft. (Airbus, Airbus People 2013)



Picture 3: Manufacturing flow chart (Gardiner 2011)

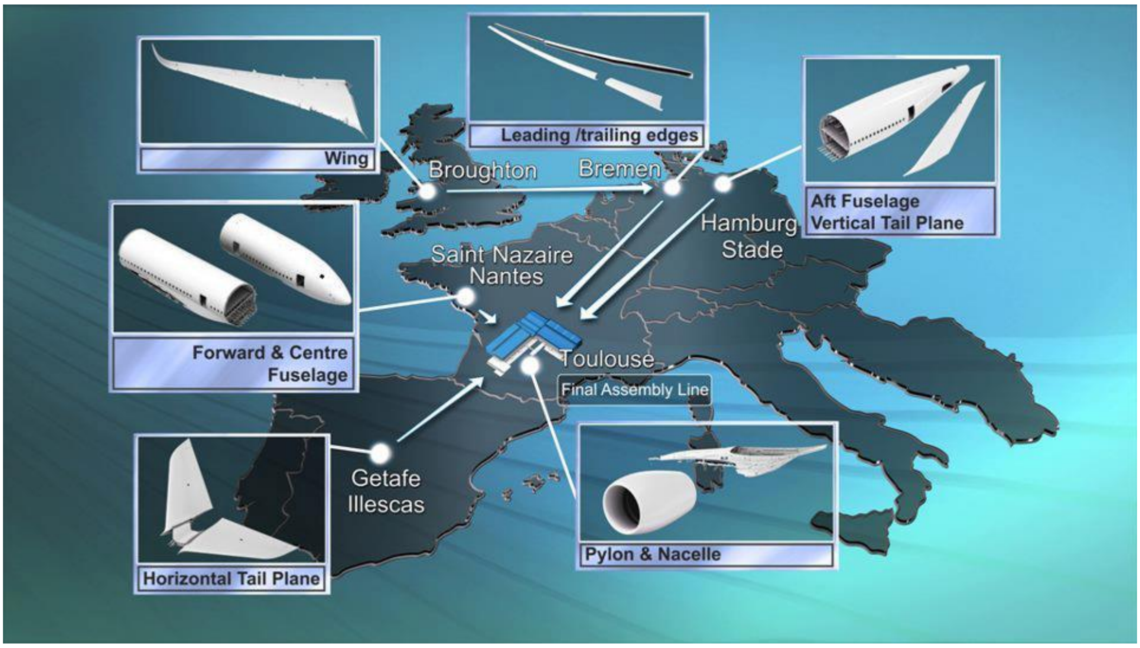
The final assembly line is located in Toulouse, France. Here, the major assemblies are joined into an optimized aircraft. Fuselage sections are equipped with large cabin parts before the orbital joints between sections 13-14 and the 15-21 and 16-19 are closed. The wings are attached to the fuselage and at the same time further items to the cabin are installed. At this point the electrical system will reach its Power-On status for the first time. Horizontal and vertical tail plates are mounted to the fuselage and the rear of the aircraft is set up. The engine pylons are the next step to be mounted and then the main landing gears. After the completions of all necessary avionic items are completed the indoor ground tests will be performed in order to prepare first flight readiness. In the meantime the cabin is customized according to the customers’ requirements. After these tests, it is the time for more tests that are made outside. The aircraft is painted and the engines are mounted and the cockpit is finalized and then the flight line phase starts. A part of the final assembly is shown in the Picture 4: Final assembly line in Toulouse. (Airbus, Airbus People 2013)

Picture 4: Final assembly line in Toulouse (Airbus, Airbus People 2013)

Before the customer handover the aircraft under goes a range of tests in flight. This is done to prevent any unwanted error in service. Every system is tested and checked in the special scenarios that occur in flight and this is not possible to be simulated or tested on ground. The customer handover is start of the service phase of the aircraft and during this phase the airline gets control of the aircraft. (Airbus, Airbus People 2013)

2.1.2 Main Component Description

The main components are illustrated in the Picture 5: A350 main components.



Picture 5: A350 main components (Airbus, Airbus People 2013)

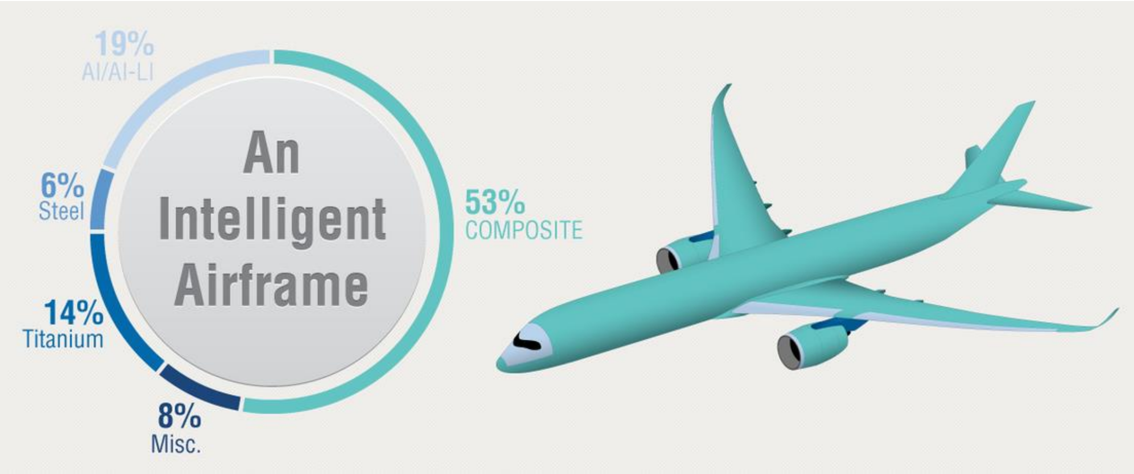
The wings are made out of CFRP mainly and for that reason some of the biggest parts that are made out of carbon fiber are the skins for the wings lower and upper covers. The wing covers are the biggest single parts that are made for civil aviation and they are about 32 meters long and 6 meters wide. All of derivations of the A350 family have the same wing but the 1000 version has a smaller trailing edge than the other ones. The aerodynamic features of the wing are the state of the art in low and high speed settings. New aspects of the wings are the adaptive dropped-hinge flaps and the droop-nose leading edge devices or in other words advanced high lift devices. The flaps can be adjusted symmetrically or asymmetrically to optimize the wing profile and also to balance the loads along the wing in an optimized way. Of course the wings and the fuselage had been under extensive CFD simulation to get the optimum performance out of the aerodynamics of the aircraft. The design was then tested rigorously at a wind tunnel to verify the results. (Airbus, Airbus A350 XWB 2013)

Airbus A350 XWB was designed so that the engines of the aircraft family can be either Roll Royce Trent XWB or The General Electric’s GE9X but no airliner has yet ordered their A350 with the GE version. The Trent XWB has a three shaft design and it’s the most efficient aero engine on the market now. The engine has an optimum internal air system that makes sure that the amount of in going air is not more than needed and this will reduce the volume of fuel needed to be burned. Rolls Royce and Airbus has done a lot of work to make the partnership successful. The Trent XWB was designed to be a low risk engine and therefore reliably and durably. (Royce 2013)

The main landing gear was designed with a new concept because of the new composite wing. With the new design economics are taken into account. The design reduces the loads lead to the wing spar and the gear beam. The main structure of the landing gear is made out of high strength titanium. There are many benefits of using titanium at this location like weight saving and corrosion-resistance. The main landing gears also have some stainless steel parts used in them which have a new kind of plating called HVOF (High Velocity Oxygen Fuel spraying). The brakes of the A350 are mad out of carbon fiber and they have better energy absorption than in past generation of brakes. The concept has fewer rotors and fewer pistons than a conventional aircraft brake. (Safran 2013)

2.2 A350 XWB Fuselage Structure

The airframe of the Airbus A350 XWB is special in many ways. The materials that are used in the airframe are advanced. A high rate of composites is used. Over 70 percent of the overall airframe is made out advanced material and overall 53 percent are composite materials. The benefit of using the composites is to get a lower flying mass and reduction of fatigue and corrosion problems. Picture 6: Material distribution shows the material diagram and where the materials are mainly used. (Airbus, Airbus A350 XWB 2013)

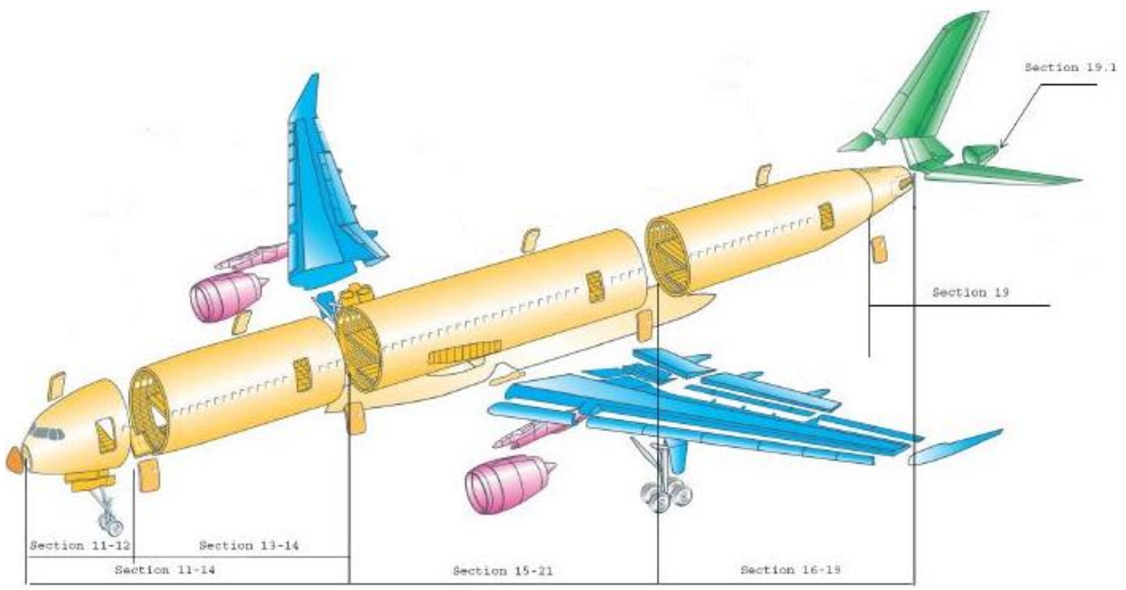


Picture 6: Material distribution (Airbus, Airbus A350 XWB 2013)

Composites are not only the advanced materials that are researched to a high level and used in the manufacturing of the A350 XWB. Aluminium-lithium alloys that are used have high performance levels and low density but the damage tolerance values of the materials are worse than the composite materials have. The compatibility between aluminium alloys and composite parts is not the best because of possible corrosion issues. The aluminium alloys are used for parts that are in a risk of getting impact damages in so called DPA. That applies to the leading surfaces of the aircraft. Some parts of the aircraft have to withstand very intensive loads cases. Titanium is a solution for carrying high loads at a low weight. The latest titanium mixes are used for the main structural elements that are high loaded frames and landing gear support and many more elements. However titanium is expensive and its use is limited to few parts only.

2.2.1 Introduction

The fuselage is designed from main component assemblies. It is divided into sections and they are show in the Picture 7: Section definition. The nose section consists of the cockpit and the first parts of cabin. It’s called section 11 - 12. This section is made mainly out of aluminium alloys and from CFRP due to high risk of strike impacts to the front surface. (Airbus, Airbus People 2013)



Picture 7: Section definition (Airbus, Airbus People 2013)

Section 13-14 is assembled from four shells and the main floor grids. Nearly all of the parts are form CFRP but some of the frames are from titanium. Critical parts on the lower shell and door frames are also from titanium due to crash worthiness requirements. The cargo door and the passenger door are re-enforced with titanium and special stringers are applied to carry the intensive loads around of the major cutouts in the fuselage. (Airbus, Airbus People 2013)

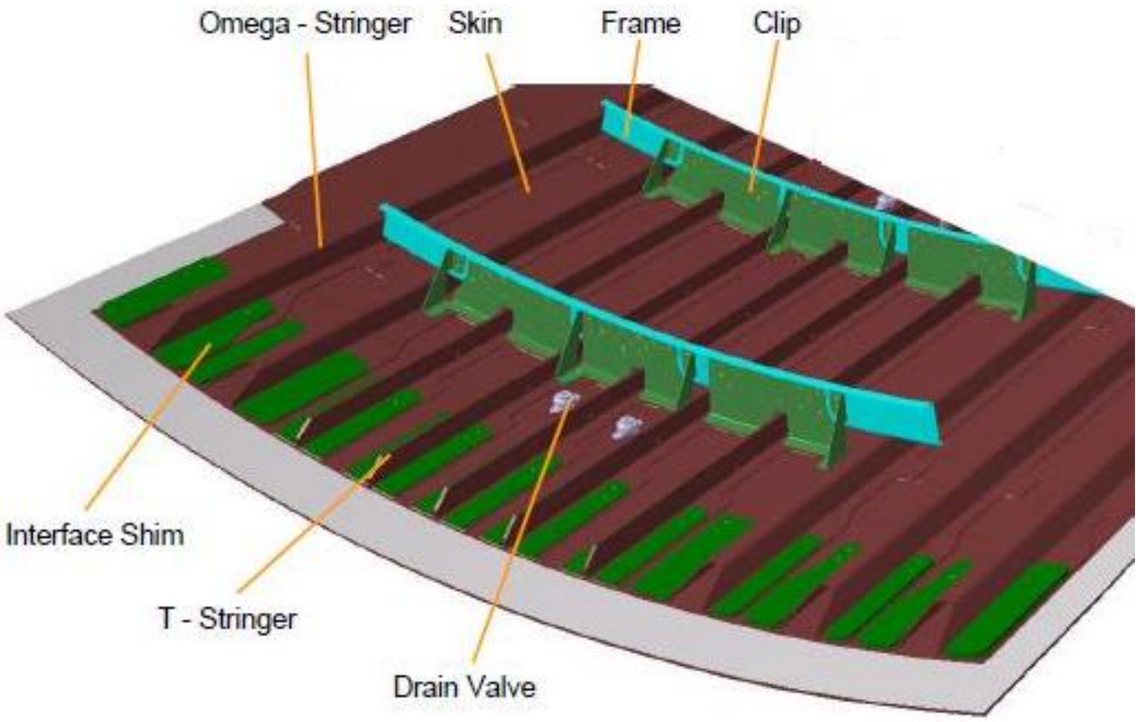
Section 15-21 is made from multiple pieces. For example the keel beam parts and the wing box that’s made out of CFRP. The section consists of the keel beam assembly and the upper shell and the lateral junction panels and the forward lower shell and the main landing gear bay and the central wing box. The wing box is made mainly from CFRP and only some spars are made out of titanium. The main landing gear bay is mainly made out of 7000-series aluminium and just some pieces are made out of CFRP and titanium. The upper shells are made out of CFRP panels and the frames are made out of CFRP. (Airbus, Airbus People 2013)

Section 16-18 is constructed from four shells and the rear end is covered with the pressure bulkhead. The lower shell is a highly loaded area because it has a lot of cut outs and there is a big size cut out to the right side shell what has the cargo door opening so the forces have to be routed around these cutouts and carried by the other parts of the fuselage but this depends on the load case that is applied. On this section there are lots of antennas and valves and operating panels, for example the outflow valve for the air-conditioning which regulates the air mass outflow. The skin and the stringers and the most of the frames are made out of CFRP. The lower part of the sections is considered as a liquid retention area and there some materials aren't allowed because of corrosion reasons. (Airbus, Airbus People 2013) (Airbus, RSDP reference structure design principles for A350XWB 2011)

Section 19 is the empennage assembly and it is designed in a different way than the other sections with the multi panel concept. The part is under high loads because the vertical tail plane (VTP) and the Horizontal tail plane (HTP). The skin of the section is made for CFRP and it is cocured with Omega-stringers. Frames are made for CFRP and titanium. A large amount of parts in this section is made out of titanium because the section has big cut outs and high loads and many attachments points. Some of the stringers are replaced by beams because the beams can distribute the loads smoother. Maintenance door support frame is integrated into the structure. The frames in this section are mainly from titanium. (Airbus, RSDP reference structure design principles for A350XWB 2011)

2.2.2 Description of the Components and their Main Functions

The main components of the fuselage section are shown in the Picture 8: Main parts of the fuselage. The picture is a general description of the parts that the fuselage is made of and some special parts like interface shims and drain valves.



Picture 8: Main parts of the fuselage (Goβmann 2012)

2.2.2.1. Frames

The frames are the main structural parts that help preventing the fuselage from buckling under compression and because they are supporting the fuselage laterally, they give the fuselage its general shape. Frames are distributing loads and when there is a cutout in the panel the frame is the main item to distribute the loads to other structural parts like the skin and the stringers. Frames also act as a crack stopper for skin in case of longitudinal tension. The frame also stabilizes the fuselage shell in case of skin failure under shear. Any primary loads in the direction of longitudinal axis are not carried by the frames neither any tensile loads due to the cabin pressure that occur in the circumferential direction. (Airbus, RSDP reference structure design principles for A350XWB 2011)

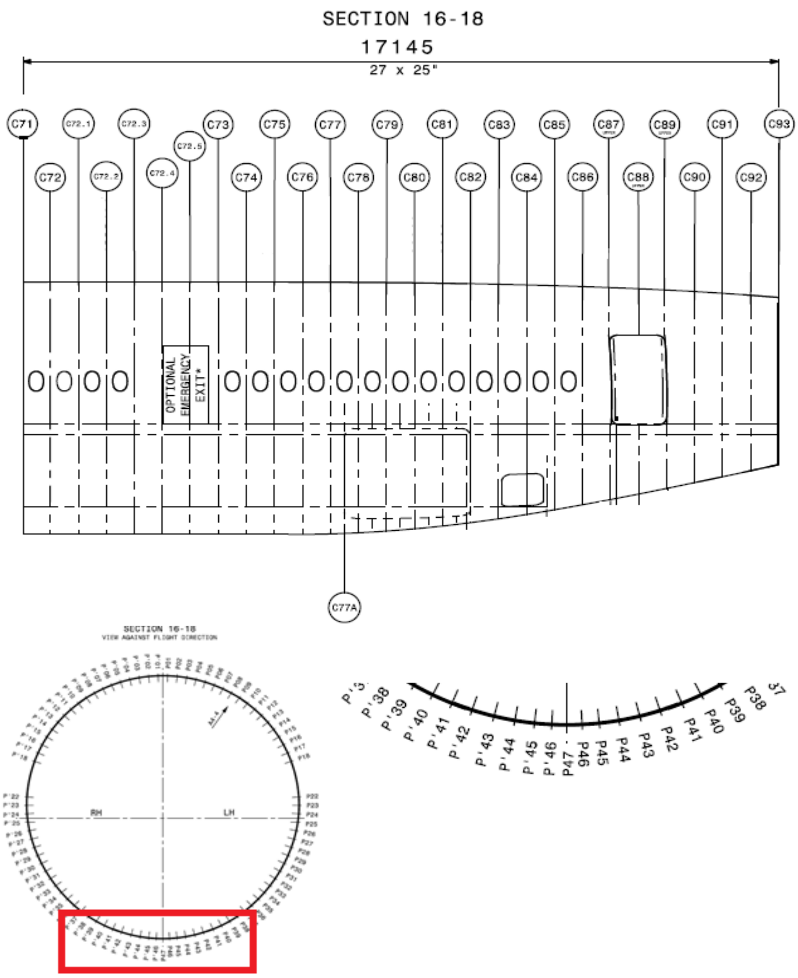
Frames are mainly manufactured from CFRP, and in special cases like in areas of the lower shell some of the frames are made out of titanium. The frame pitch within the Airbus A350 program is 635 mm and it is set in the master geometry. The frames have geometrical constraints that define their shape in the aircraft to their current shape. The CFRP frames are made with ATL. The ATL drops the plies of pre-preg on the tooling surface and presses the plies on to the tool. The frames are cured in an autoclave and after demoulding they are milled to their final shape. (Airbus, RSDP reference structure design principles for A350XWB 2011)

Z-shape frame are used in on the A350 and there are many reasons for using this shape like low cost of manufacturing and lightweight design with the desired stiffness. The frame has to be easily attachable because the frame is cut and attached at the longitudinal joints. The Picture 9: Frame mold will illustrate the shape of the mold that the frames are made with. This kind of open mold solution makes it possible to manufacture the frames with ATL. The frames are named by their location on the aircraft and the Picture 10: Stringer and frame naming against flight direction shows where witch frame is located and in the same picture the stringer naming is shown. (Goβmann 2012)

Picture 9: Frame mold (Goβmann 2012)

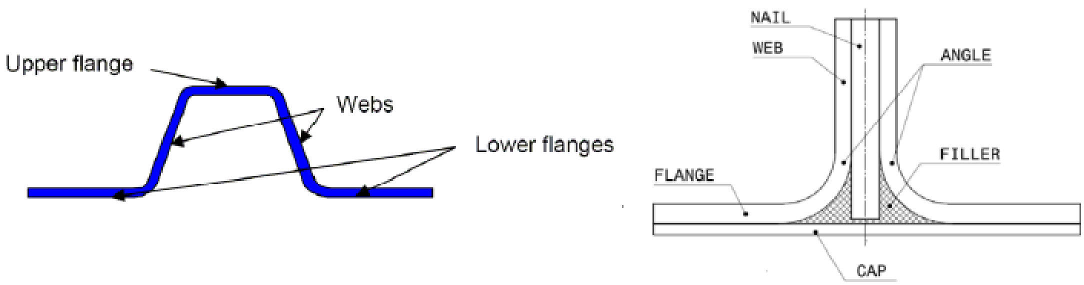
2.2.2.2. Stringers

The stringers are the part that carries the loads in the longitudinal direction and also add bending stiffness to the skin. There are two different cross sections to stringers Omega-stringers and T-stringers. Baseline for the A350 program is the Omega-stringer but T-stringers are used in locations that need more stiffness in less width. The different concepts of stringers have their advantages and disadvantages like tooling costs and manufacturability or weight to stiffness ratio. The stringer naming is shown in Picture 10: Stringer and frame naming against flight direction. The stringer naming is described in the picture in a way that the view is against flight direction. (Airbus, RSDP reference structure design principles for A350XWB 2011)



Picture 10: Stringer and frame naming against flight direction (Airbus, RSDP reference structure design principles for A350XWB 2011)

The stringers types have some constraints concerning geometry. The pitch varies due to the type of stringers and to the dominating loading. Also the alpha angle of the Omega-stringers is set to have the maximum bending stiffness. The stringers are manufactured with the ATL machine, only some additional layers have to be laid up by hand. The T-stringers have nail fillers that contact the three parts of the T-stringer the webs and the cap. Before the stringers are bonded to the skin they are milled to their final shape. The stringers general shape and the names of the different parts are named on the Picture 11: Stringer part naming. Both stringers have webs and they are the main part that makes the stiffness to the stringers. (Airbus, RSDP reference structure design principles for A350XWB 2011)



Picture 11: Stringer part naming (Airbus, RSDP reference structure design principles for A350XWB 2011)

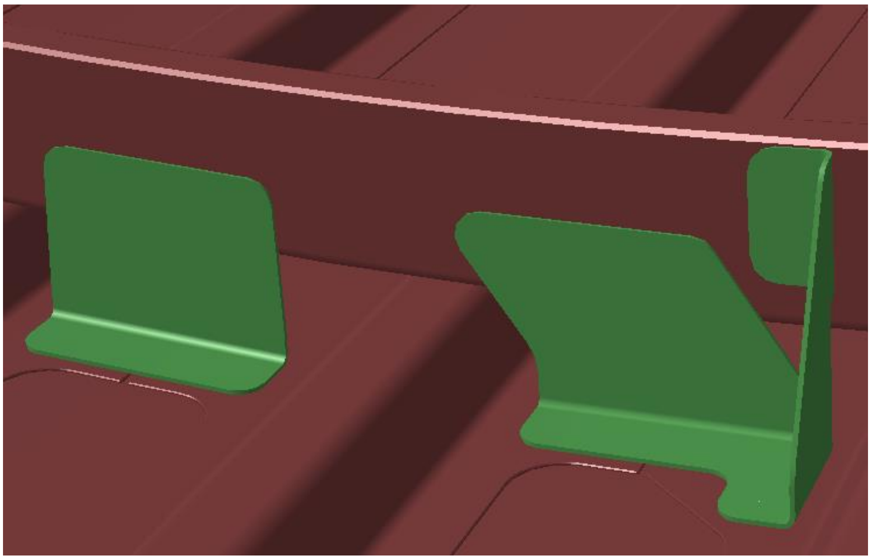
2.2.2.3. Clips

The clips are the part that attaches the frame to the fuselage panels and they also support the frames from buckling. The clips are loaded with three types of loads:

- Compression linked to the depressurization of the fuselage
- Shear due to torsion of the fuselage and bending of the frame
- Twisting of the frame introduces loads in the direction of longitudinal axis

There are a lot of clip types but they all have the same idea in simplicity. The clips can be stabilized by cleats / stabilizers and they can be integrated in to the clip or they can be added in later. (Goβmann 2012) (Airbus, RSDP reference structure design principles for A350XWB 2011)

Clip manufacturing is done with a special process using CFRT as material. In special cases the clips can be made out of titanium because of its better properties. The CFRT ones are made out of two matrix materials PPS and PEEK, PPS is used as a baseline but PEEK can be used if local stress requires it. The basic idea of CFRT is having a special type of resin that can be reformed if pressure and heat is applied. Because of heat differences inside the aircraft the material is not useable in all locations. The clips are bended in a single motion. The titanium ones can be bended or milled into shape depending on the design and the thickness requirement of the clip. Assemblies of clips can be from different materials. Within the Picture 12: Clip example is shown. (Airbus, RSDP reference structure design principles for A350XWB 2011)



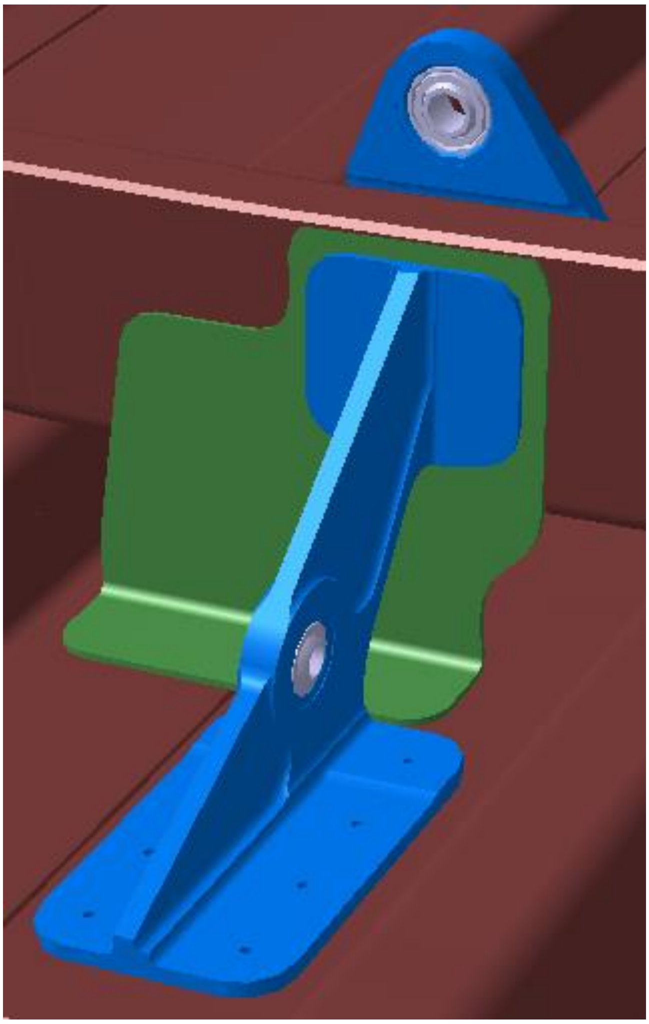
Picture 12: Clip example

2.2.2.4. Panel

The panel is constructed from two main elements: stringers and the skin. Skins main function is to isolate the outside air and make the fuselage possible to be pressurized. The skin carries the loads that the cabin pressure produces. In the past you could notice that the skin was the pressure loaded part because the skin was flexing and pushing outwards because of the pressure difference. The panel is a stage of manufacturing the shell and the following stages are in the chapters 2.2.2.6. (Goβmann 2012)

2.2.2.5. Brackets

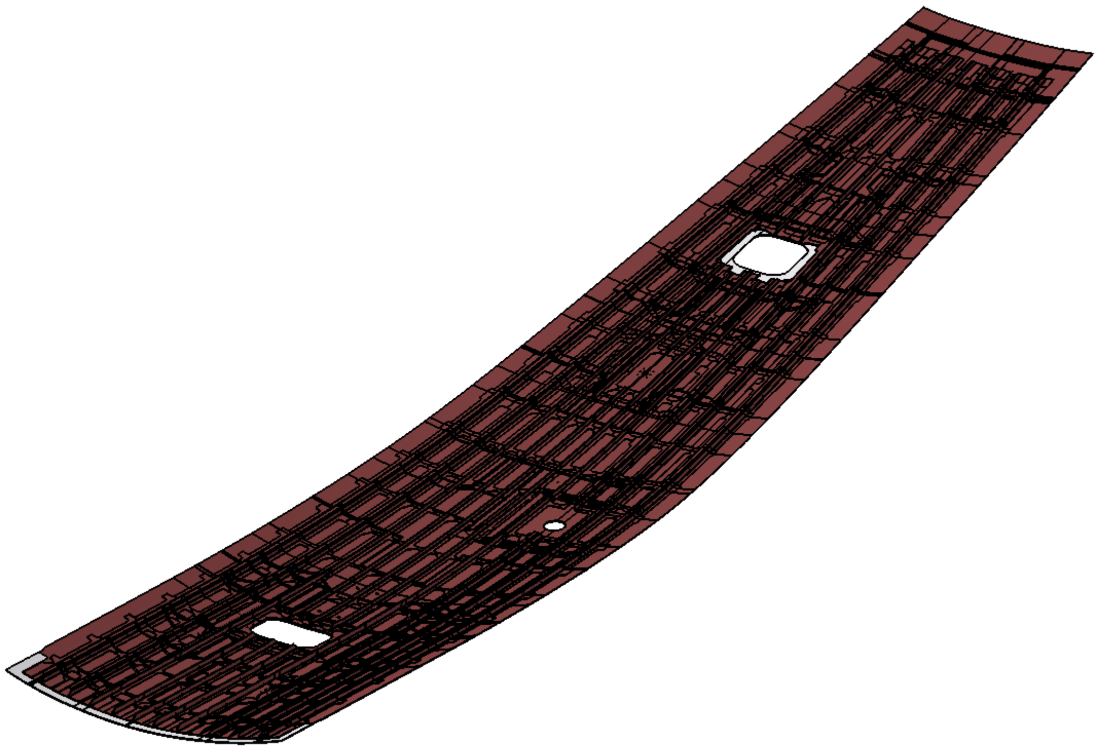
A brackets main function is to attach a desired component for example cables, ducts or insulating mats to the fuselage. The brackets can be bonded or riveted to the main structure. Some brackets can be attached to different structural components like beams and struts. The brackets are divided into ATA chapters. Typically brackets vary in design but as an example a bracket is shown in the Picture 13: Bracket example. (Goβmann 2012)



Picture 13: Bracket example

2.2.2.6. Machined Panel

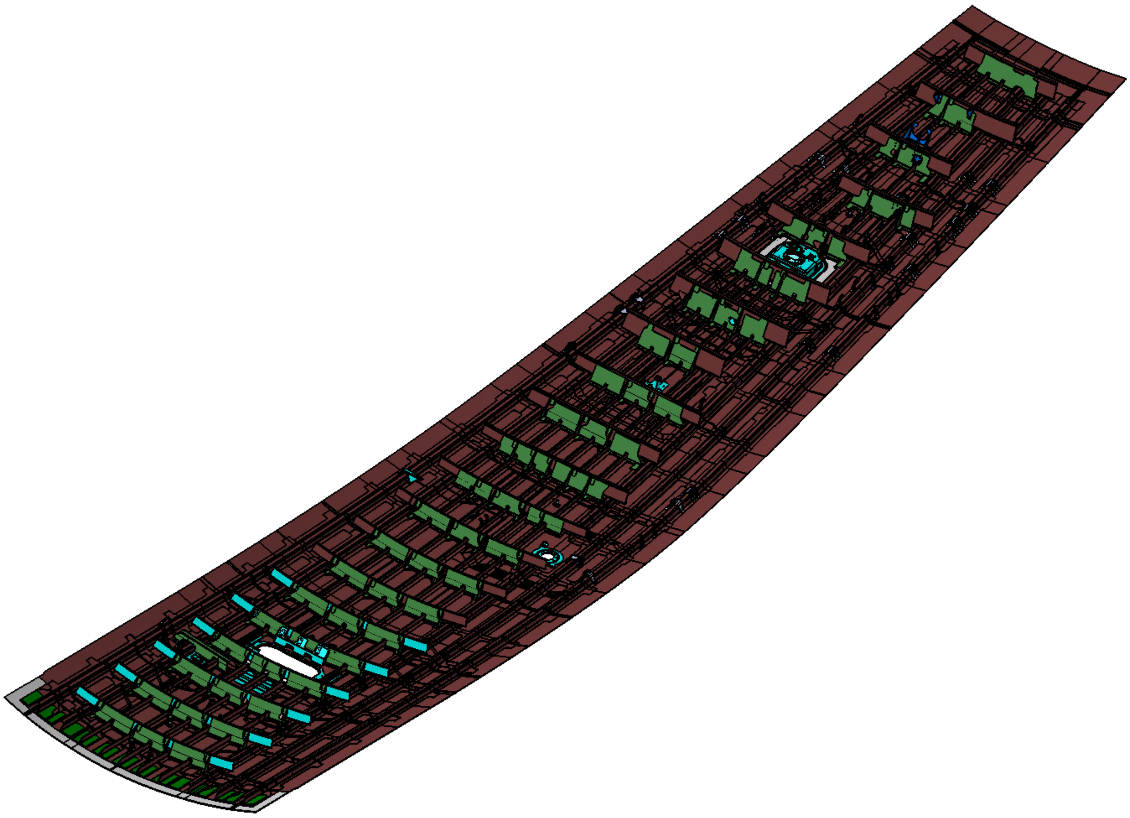
The skin is made out of CFRP layers and the stringers are positioned on the uncured skin. They are cocured afterwards to get the most advantages out of the joining of the two elements. The CFRP as a material makes some constraints to the shape and the size of the parts because it's not possible to bend the layer to every shape without having cuts made to it. The panel parts have to be milled into shape and this has to be made also for the cobonded part. The cobonded part is 10% bigger than the part that is used to assemble the section. This is because of the manufacturing constraints of the CFRP for example orientation errors of the fibers and the lacking of resin on the edges of the part. Edges are trimmed and cutouts are done and also the holes are drilled and then the part is called machined part which is ready to be assembled. A machined panel is shown in the Picture 14: Machined panel.



Picture 14: Machined panel

2.2.2.7. Assembly of a Shell

As an example of how the shells are manufactured, the lower shell of the A350 is manufactured in different stages. Every shell is based on a machined part of a skin and stringers where the items like brackets and clips are attached. The assembly of frames, clips and brackets is done with the help of jigs which can be positioned so the items on the shell are in the right place. The frames and the clips are riveted to the skin but before the clip is riveted to the panel it needs to be shimmed and so that the build tolerances are taken into account. An assembly picture of a shell is shown in Picture 15: Shell manufacturing.



Picture 15: Shell manufacturing

3 DESCRIPTION OF BASIC PRINCIPLES

3.1 Methodology Used in Engineering

There are many methods used in engineering because different methods can be more valuable to different engineering tasks. The methods have been developed so that engineering level would grow and grow and there is always a step that can be taken so every time there is no need to start from zero level. There are methods for nearly everything and for engineering there is a possibility to combine methods from different branches of methods for instance creative methods are a very good example that they can be used for creating ideas for concepts of engineered parts.

The benefits of methods are that they save time and they also guide the tasks. Different methods have their own benefits and also their disadvantages. Depending on the task at hand the methods should be selected and modified if needed. For instance some parts of methods can be skipped or assumed that they aren't so valuable or important for the task. There are many methods to develop parts for example the systematic development of a part is a large scale methods which takes a lot of variables into consideration. The basic principle is nearly the same with a lot of the methods and this is that a concept idea of a part already is but it needs to be researched which is the best possible solution for the task. The VDI 2221 is a well-known development method guideline and this is explained more in detail in chapter 3.1.1 and this method is used to develop the coupling concepts. (VDI 1987)

There are hybrid methods of development used in some tasks because sometimes there is no reason to apply the entire method. It can be the case that the method doesn't take into account something which is important and therefore a different method is applied to some stages of the development. For example the trial and error method is not the method to use in a complex and expensive task but it can be applied as a part of systematic development method because the concepts that are developed in a systematic way can also fail although it's unlikely.

There is a very similar method to the VDI 2221 guideline and it's called new product development. It can also be applied to many tasks with topics from engineering to business and to many more fields of task solving. The development method is divided into eight stages which are:

- Idea generation
- Idea screening
- Concept development and testing
- Business analysis
- Beta testing and market testing
- Technical implementation
- Commercialization

The development method is a general guide how to start and what stages are needed to be taken into account before the task is completed. The method is more about creating possible solutions to a problem than researching intensely the problem and then creating the solutions. (Mentation 2012)

Value analysis is a six stage job plan process that outlines the procedures that have to be defined but the stages don't outline the methods that are to be used in the stages. The process is divided into three main stages pre-studies, main study and post-study. The process of the main study is divided into more detail to:

- Information
- Function analysis
- Creative
- Evaluation
- Development
- Presentation

The value analysis is used in many fields for example in business and engineering. The analysis is driven that the product gains more value in its requirements. The value analysis is usually used in teams and the team leader needs to have knowledge about the method itself and about the task where the analysis is applied to. (VP Education 1997)

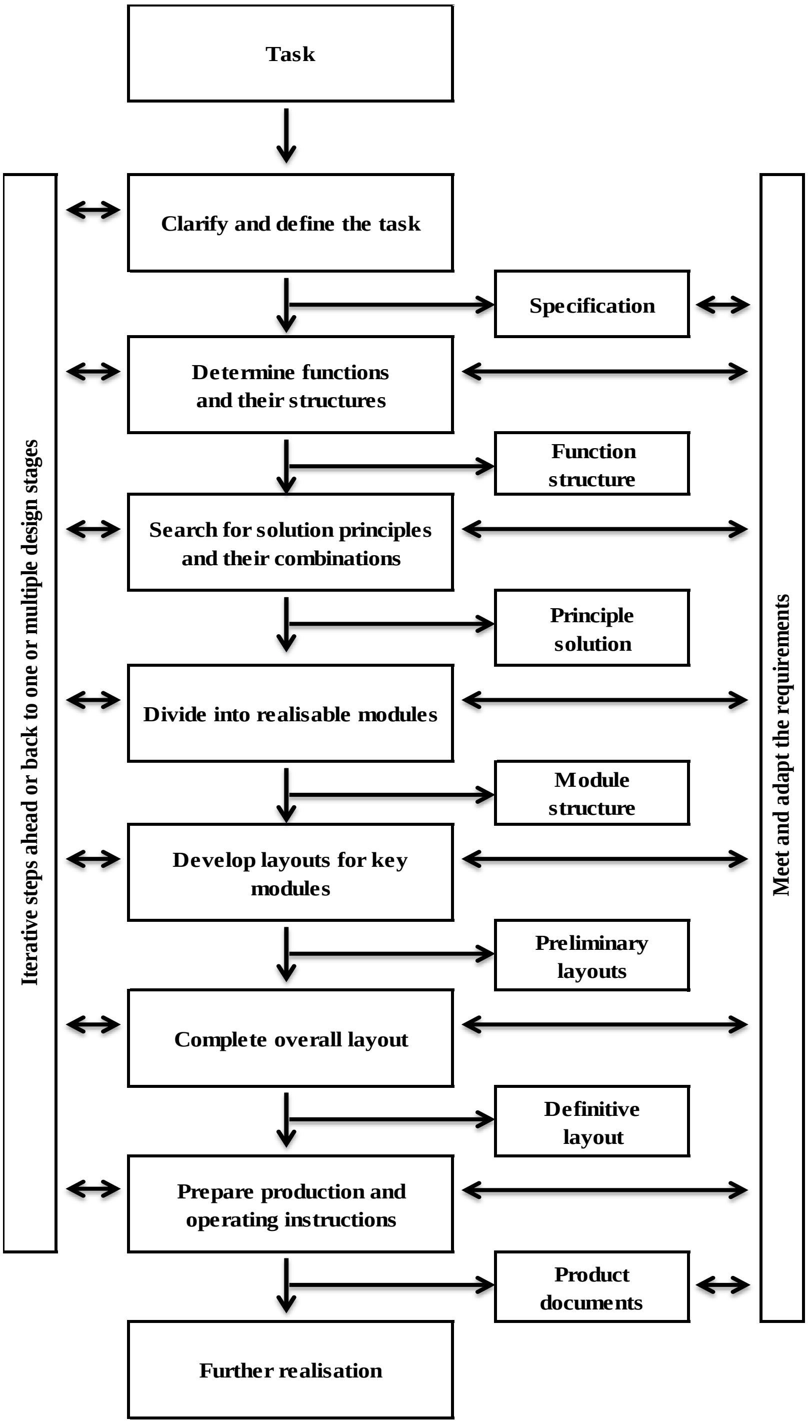
3.1.1 VDI 2221

VDI is the abbreviation of Verein Deutscher Ingenieure, which is a German engineering association, one of the biggest of its kind in Europe. Its aim is to standardize procedures in engineering and production and it publishes its research in form of guidelines and standards. (VDI 1987)

VDI 2221 guideline is a description of a systematic approach to a design problem of a technical system or a product. The document was created in the late 80's and it has gotten recognition from the engineering society and the educational side as well. The guideline collects the most notable principles for product development. The concept of the guideline is that of a systematic problem solution. Define the main problems and dividing them to subproblems and create subsolutions and combine them to get solution for the main problems. (VDI 1987)

The benefit of using this guideline is that it can be used to its full length or it can be adapted to any desired extent. The guideline describes the full product development process and advises on what methods can be used in the stages of the process. As an example for developing solutions ideas it's possible to use the well-known brainstorming method or not so well-known method of provocation where picture, key words and questions that can be answered to trigger the mind to formulate more ideas. The VDI stages are shown in the Table 1: VDI 2221 process tree. (VDI 1987)

Table 1: VDI 2221 process tree



The guideline can be found from well-equipped public library or from technical university libraries. Also it is possible to buy the guideline from several standard providers. Parts of the guideline are used in the development of the coupling concept and they are shown in chapter APPLICATION OF THE VDI 2221. (VDI 1987)

3.1.2 Creative Techniques and Other Used Methods

Brainstorming is an effective solution creation tool that is used on groups to get innovative solutions to a targeted problem. It was created in the 1939 and from then it has been used to create solutions to different kinds of problems and this method can be used in every field. The group that is attending the brainstorming session has to be carefully selected, so that the brainstorming will be productive. Within the group they should be well informed on the problem that they are going to create solutions to and also that the group should be open for new ideas because in this way new innovative ideas can be created. In the first place brainstorming is a tool to discover possible solutions to a problem and the solutions should not be judged when they are suggested. Outside of the box thinking should be encouraged and solutions can be adjusted to create new idea and also ideas can be built on one other like a house of cards. (Hyde 2005)

6-3-5 method is a creativity technique which is based on brainstorming method. The idea is to create multiple solutions to a problem by mass producing solutions. The concept is to have 6 participants in a meeting room and they create 3 ideas every 5 minutes. The solutions are written down on paper and after 5 minutes they are passed on to the next participants to use it as an inspiration. Over a hundred solutions are created in under 30 minutes. The method wasn’t used because of the complexity of the task. (Rohrbach 1969)

A survey is a study that is documented and assumptions are made from the statistics of the results. Surveys can be produced for every aspect of things but the configuration of the survey is important because the results are affected on the configuration. Also the surveys participants in more demanding surveys have to be selected so that they have background on the surveys subject so the results of the survey are reliable. From the surveys the results can be divided into sections which were used in this task to gain more clarity in the task.

The 3-criteria evaluation method selects three level of requirement fulfillment. The three levels can be different in different requirements but sometimes it’s good to keep the level simple and concentrate on the assessment. The assessments of the concepts with the 3-criteria assessment were done in different ways some requirements have 5 levels of fulfillment and some have only two levels of fulfillment.

Go/no go assessment is a noncritical assessment tool where a go is applied if the requirement can be filled with the solution that is applied. If the requirement is too complex or doesn’t fit the requirement parameters or it cannot fill the requirements a No go is applied. The go/no go assessment is usually used in nonessential aspect due to its simplicity.

3.2 Stress Theory

The stress theory is divided into two main parts. The chapter 3.2.1 describes the hand calculations and explains the theory behind the calculations. The chapter 3.2.2 describes the FEM calculations that are made for the research of the coupling concepts ability to function as it should. In the coupling there shouldn't be load peaks but smooth force flux in the entire coupling. The calculations are made with the material data and the load case data that Airbus has defined for their stress calculations.

3.2.1 Principles of Hand Calculations

3.2.1.1. Fastener Amount

The needed amount of fasteners has to be calculated and therefore the applied shear stress is calculated for the rivets. To calculate the applied shear stress that comes to the fastener systems, a stress equation is used where the force is divided to the area of the fasteners that carries the force. The force that has to be carried is divided by the amount of rivets used and the area with this rivet force is divided is that of the fasteners cross section with is considered as a circle. The equation is for this kind of calculation is the Equation 3.2-1. (Airbus, HSB Handbuch Struktur Berechnung 2007)

$$\sigma_{App.Shear.Rivet} = \frac{\frac{F_{Rivet.SU}}{n}}{\frac{\left(\pi d_{fastener}\right)^2}{4}} \qquad \text{Equation 3.2-1}$$

3.2.1.2. Buckling

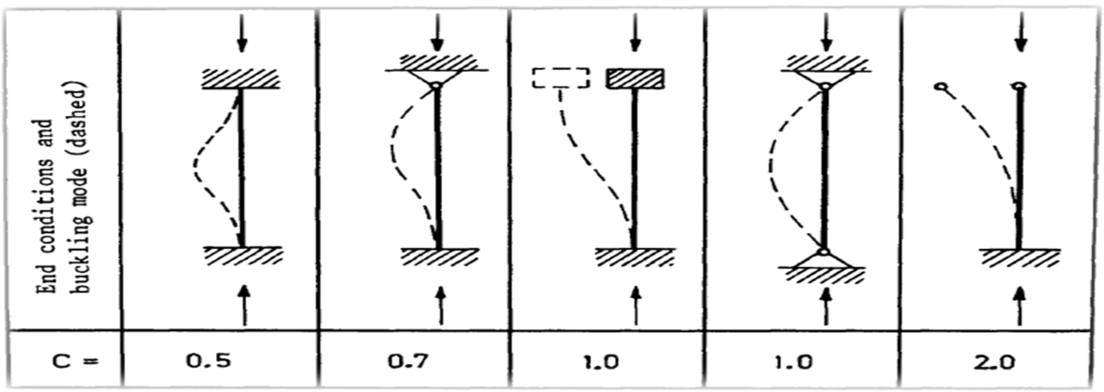
Calculation of compression buckling stress has to be calculated because the most critical load case is compression. The Equation 3.2-2 is used for calculating the compressive buckling stress. The equation calculates the needed stress to make the column buckle. The equation takes into account the modulus on elasticity of the material that is used. When composites are applied the E_c must be changed to the E module which is under interest because the composites have multiple E values. (Airbus, HSB Handbuch Struktur Berechnung 2007)

The equation is a combination of tree equations. The i value is a ratio value of the second moment of area and the cross section area from which is a square root value taken. The L_e is the length of the column multiplied with an effective length factor. The Equation 3.2-3 and Equation 3.2-4 have the definitions of the i and L_e in equation form. The effective length factor depends on the supports of the column and the different cases are explained in the Picture 16: Effective length factor C. The HSB method 41100-01 is applied to the calculations. (Airbus, HSB Handbuch Struktur Berechnung 2007)

$$\sigma_{Compression\ buckling} = \frac{\pi^2 E_c}{\left({}^{L_e}/_{i} \right)^2} \qquad \text{Equation 3.2-2}$$

$$i = \sqrt{I / A} \qquad \text{Equation 3.2-3}$$

$$L_e = CL \qquad \text{Equation 3.2-4}$$



Picture 16: Effective length factor C (Airbus, HSB Handbuch Struktur Berechnung 2007)

The comparison of the different concepts is done with RF values and to get an RF value the applied stress has to be calculated. The applied stress is calculated with the Equation 3.2-5. With the Equation 3.2-5 the force is divided on the cross section and this is the stress that is applied through the column. There can be times when the load is divided into pieces and then some assumptions have to be made, the areas can be combined or shared. RF factor in this case is calculated by dividing the allowed stress with the applied stress and this is shown in the Equation 3.2-6. (Airbus, HSB Handbuch Struktur Berechnung 2007)

$$\sigma_{Applied} = \frac{F_{Compression}}{A_{Cross\ section}}$$ Equation 3.2-5

$$RF_{comp,buck,hand} = \frac{\sigma_{Compression\ buckling}}{\sigma_{Applied}}$$ Equation 3.2-6

3.2.1.3.Compression

The compressions applied stress is calculated with the Equation 3.2-5. The allowed stress is coming straight from the material properties. They are compared with the help of RF which are calculated by dividing the allowed stress with the applied stress. All the same assumptions are used in the compression calculations as in the buckling calculations. This calculation is less critical than the buckling calculation because the equation takes less concept properties into account. The RF is calculated with the Equation 3.2-7.

$$RF_{Comp,hand} = \frac{\sigma_{Compression}}{\sigma_{Applied}}$$ Equation 3.2-7

3.2.1.4.Sizing Loops

To have a reasonably comparison of the concepts, the RFs or the weights of the concepts have to be the same and it is simpler to have the same weights and then compare the RF values. Its simpler because the RF are taking into account the geometry of the concepts and the secondary moments of areas and the material properties and to get all of them to be constant is more complex than having the thickness as a changing property.

With the thickness as a variable it is simple to get the weight as a constant because the desired weight is known which comes from the driving concepts weight and the areas of the concepts are known there the thickness is applied to and the material properties of the concepts are known. The Equation 3.2-8 shows the relations of the characteristics of the same weight calculations.

$$m = \rho A h \qquad \text{Equation 3.2-8}$$

3.2.1.5. Best Concept and Material

The best concept in geometrical vise can be calculated by applying the same material to every concept and the same weight and then calculating the RF results of the cases that are inconsideration. For the material, titanium was selected because it is the most simple and the most interesting option to use because the material properties are taken from a very reliable source and also because the properties do not chance when the thickness varies in a small scale.

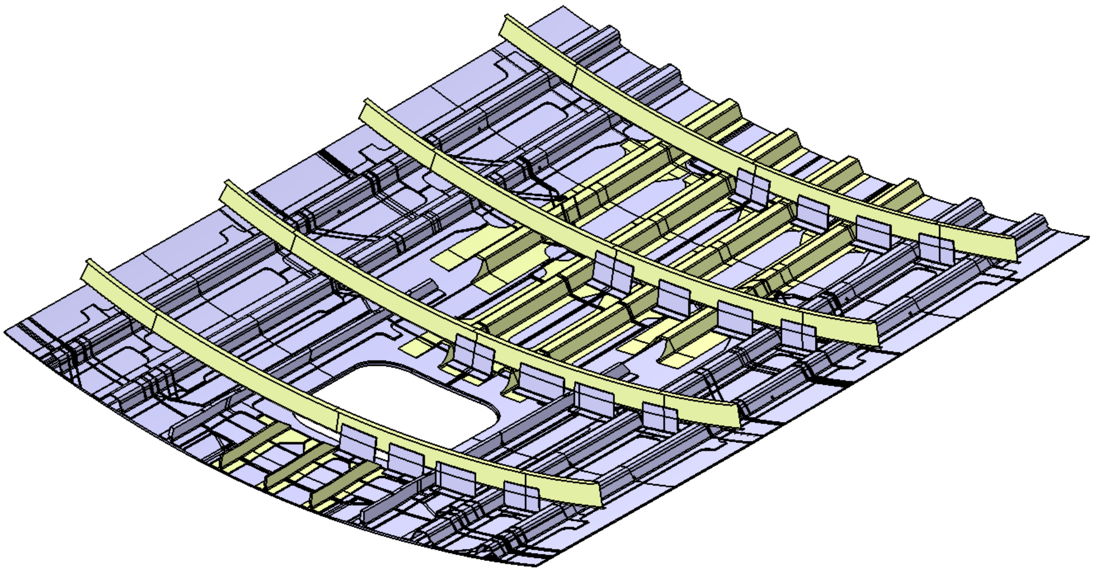
For the best material, the material properties and their densities come into question. The material properties can be compared directly at the values but they have their differences in weight. Due to this they had to be applied to one of the concepts to get a comparison of the best material selection or the properties can be compared if the densities are taken into account but the real case solution gives more perspective to the differences that will accrue in the concepts that are under analysis.

3.2.2 FEM Calculations Principle

FEM is an abbreviation for a finite element method and it’s a method to calculate stresses and displacements and other aspects that can be calculated from an element model. The finite element method uses element equations to calculate the relations between the different elements and nodes. The equations are defined in set and the set are combinations of nodes and elements. Every element and node has an equilibrium equation and if this is not the case the grid nodes creates a singularity in to the output file that the calculating program creates which is in this case MSC NASTRAN. The use of a solver program is needed due to the complexity of the environment.

The mesh can use 1D, 2D, 3D, 4D elements. The 4D element has the time stamp on the element but they are not used in this case. The mesh contains every component that needs to be calculated. The mesh needs to be constraint and also loads needs to be applied. The constraints need to be as close as possible to the real case scenario to get accurate results. The materials and material properties need to be the same as in real life that the results are consistent to the real situation as possible. The FEM is not an accurate tool to make certain that the structure holds the loads that it should hold. Therefore large scale real size testing has to be done so that the stress calculations can be confirmed.

The environment for the calculation of the coupling is larger than just the frame bay of the coupling area. To see what kind of loads the coupling has to withstand a large environment had to be created. The environment was defined by the GFEM model because the loads that are applied to the GFEM are also applied to the DGEM. The displacements on the GFEM that happen at the boundaries of the environment are applied to the DFEM. The environment that is used for the calculations is shown on the Picture 17: DFEM environment. The clips are mirrored at the symmetry line at the lowest point of the shell.



Picture 17: DFEM environment

4 TASK DESCRIPTION

As shown in chapter 2.2.2.2 different stringer types are used in the A350 with respect to their load cases applicable on the contrary, design and manufacturing constraints lead to the not optimized use of stringer types in the certain areas for example an Omega-stringer may be too wide to travel a planned path and T-stringer may be necessary in this location not due to that it's not so wide. In the A350-1000 concept phase stringer locations have been identified in which a change from one stringer type to the other would be beneficial in terms of design and cost. However, simply cutting the stringer will induce peaks into the force distribution in the panel so there is a need to have a coupling device to optimize the force flux. This thesis describes the development of a coupling concept from a T-stringer to an Omega-stringer with a systematic approach.

The coupling development will give possibilities to make a better design by giving more freedom for the design. A well-recognized systematic approach to product development is the VDI guideline 2221 and this guideline was applied and adapted to this task. The guideline will help to make the best systematic solution and the guideline will provide methods and process descriptions.

In this case is important to apply stress analysis to ensure that the design is working without failing. Preliminary calculations and FEM calculations are done so that the designed coupling concepts can be comparable. Stress aspects are most important for this case and they have to be researched to pin point what is the best coupling concept. The definitive air worthiness stress calculations and verifications are not part of this thesis because of the extraordinarily high workload.

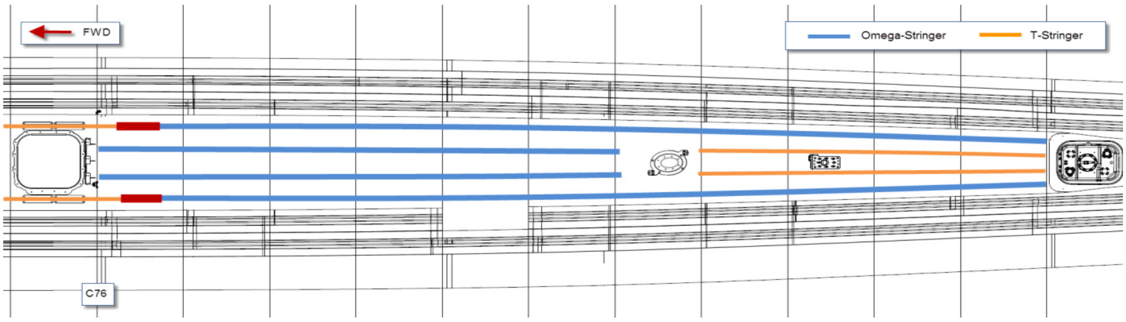
Desired goal for this task is to get the optimum solution for this task and research the limitations and requirements. The limitations and requirements are researched and collected in this thesis. These limitations and requirements are defined with values of importance which are:

- Must
- Good to have
- Shall

The areas that the coupling might occur are described and the load cases are explained and the environmental requirements are collected. To get the solution assessed correctly the following assessment methods are used, value analysis and the 3-criteria evaluation. Brainstorming within our work team is used in the development and assessing process.

The placement conditions of the coupling can be in any location of the fuselage and there are some couplings that have been designed and used in the aircraft. The designs cannot be used for this application purpose because they are design for in lined cases and for the same types of stringers that are coupled. The location of application was thought to be with in the lower shell or in the orbital joint area where the keel beams are coming and that could be switched to Omega-stringers for design and cost reasons.

The locations are one of the most loaded areas in the fuselage because of large cut out for cargo door and other additional items that are located on the lower shell. The spot of the lower shell has some interesting conditions that make the coupling of stringers at this location very beneficial. At this location the stringers are misaligned but a coupling would be an enabler for a harmonized stringer distribution towards the end of the section. The location is between C76 frame and C77 and the stringer that would be cut and coupled is the P45. The Picture 18: Concept setting of stringer shows the concept idea of having Omega-stringers in the lower shell. The red arrow shows the flight direction and the red boxes show were the coupling of the two stringers would take place.



Picture 18: Concept setting of stringer (Ochsendorf 2012)

The lower shell is in an area that liquids are collected and because of this it’s the optimum conditions for corrosion to appear. Therefore some of options are not possible to be used. There is a material list that has the approved materials for the A350 program and the materials that are going to be used for the concepts have to be selected from this list.

5 APPLICATION OF THE VDI 2221

5.1 Clarification and Definition of the Task

The first steps of the application of the VDI 2221 guideline are clarification and definition of the task. The task is cleared in the aspects that define the coupling concepts and the aspects that have to be taken into account. The preliminary studies are the things that are done in the stage one and they are done so that the result of the development is as close as it can be to the desired end product. This is the first stage of the VDI 2221 guideline. (VDI 1987)

Background to this task was that a research was made and from that it was concluded that the options are worth researching more. As a stringer coupling is a facilitator for optimum stringer layout. Because the locations of uses are in a highly loaded area its essential to make a DFEM calculations to make sure that the coupling concepts are able to handle the loads that the environment creates to the coupling. The possibilities of different coupling concepts are at test and to evaluate then DFEM is needed because of highly complex shapes that have to be taken into consideration. The DFEM environment has to be larger than just the coupling area because the surroundings of the coupling are also a point of interest.

The task has to be clearly defined because if this is not done the task might take an unwanted direction. This will minimize the amount of rework that needed to be done and the amount of loops needed to develop the concepts. This in the end will result to less time and resources used to develop the desired results.

The requirements of the coupling are to be researched to make sure that the coupling meets them in the end. The limitations that are defined in the RSDP have to be met. Within the requirements it came up that air worthiness is not the target of the design and for that more research has to be done. Air worthiness had to be taken it to account in every turn still because that is essential.

In order to create a good requirements list a workshop was held where we used brainstorming to create a requirements list that takes many points of view into consideration.

General Airbus requirements have been stated in the RSDP and they are taken into consideration. These workshops been performed with the rules of brainstorming and this results to outside of the box solutions and requirements. Finally more than 20 requirements have been taken into consideration. For more structure, the requirements were divided into sub-requirements and as sorting themes the following were used, stress, geometry, product, manufacturing and environmental conditions. In the next step, a value grid was created with every category and with every requirement in it which will be used later when assessing the concepts. Which has the largest value is the most weight on the design of the coupling and vice versa. The Table 2: Requirement list has the results and the table is color coded so it will be easier to follow in the next stages.

Table 2: Requirement list

Stress
Carry load (RF 1)
Stability Stiffness (RF 1)
RF bigger 1.0
Airworthiness (Refer to Far part 25)
Fatique (280000 Flight Cycles)
Load Cases (All load cases)
Crash worthiness (Refer to Far part 25)
Thermal expansion (Load cases and Thermal Cases)
Geometry
Max dimentions
Max Lenght (610 mm)
Max Height (41 mm)
Max width (127 mm)
Overlapping (45-50 mm)
Couple Delta Height (No gaps)
Clip assembly (Max lenght takes this in to account)
Butt-strap Delta height (Max 7 mm)
In-line / Un-line (max un-line 90mm)
Product
Weight (0 weight gain ideal (0.5kg))
Cost (Cheap as possibly)
Material (Certified material list for the A350 project)
Build principle (Defined at the concepts)
Multi Functions (No)
Enviromental Conditions
Corrosion (Refer to RSDP Volume 1 Chapter 7)
Surface protection (Refer to RSDP Volume 1 Chapter 7)
Electronic bonding (Refer to RSDP Volume 1 Chapter 8)
Lightning Strike (Refer to RSDP Volume 1 Chapter 8)
Fire worthiness (Refer to Far part 25)
Manufacturing
Installation time (no increace on sequence leed time)
Assembly sequence (Shell assemble)
Communality (Design for A350-1000)
Tolerancing (Defined in Detail Desing)
Joining principle (Research)
Functional
Drainage (3 mm Clearence)
Inspectability (Refer to FAR part 25)
Repairability (Refer to FAR part 25)
Temperature range (-50 to 90 C)
Harmless to other parts (Primary structure other are redesigned)
Recycling (Material list options)
Pressure range (Presurized)

From the requirements the most and the least effective requirements were selected by evaluating the requirements in a survey. The most important ones define the coupling in its design but all of them have to be met. The least effective requirements are taken into consideration but the thoughts are focused on the other requirements. They are shown on the Table 3: Most important and the least important requirement.

Table 3: Most important and the least important requirement

Most	Least
Air Worthiness	Assembly sequence
Rf bigger 1.0	Harmless to other parts
Carry load	Recycling
Stability / Stiffness	Pressure range
Weight	Multi Functions
Cost	
Max dimentions	
Max Dis aligment	

The stress category has several requirements that have to be verified with the help of computer assisted simulations. The first one to come up was that the coupling has to carry load what is self-explanatory. The RF has to be over one but close to it to make sure that the coupling is optimized in weight. Air and crash worthiness of the coupling concepts is not the objective of this thesis due to their high workload. The fatigue problem when talking about aircrafts is not an easy subject especially because the concept is design for an A350 due to its new concept of using mainly CFRP. Thermal expansion is taken into account at the load cases.

Geometry requirements are defined but some of them can vary due to the design of the concepts. Maximum dimensions are set and they come from stringer and frame pitches and also from the skin to the lower flange of the frame. The overlap distance of the coupling with the two stringers is taken from the RSDP and the value is an Airbus stress requirement. The stringers feet have different levels and they have to be leveled out. The design was meant to be done so that the stringers are not aligned because from that it’s easy to change it to an in-lined version.

Product category has the requirements that are describing the couplings properties. The weight neutral solution state that the cost is not fixed only to the coupling because there is a cost reduction due to the stringer change. The complete cost evaluation will not be a part of the thesis. The cost of the coupling is evaluated in quality. Cost is always a factor in everything but with different manufacturing methods used there are different prices. The material selection is also very vital because it has effect on everything. Also the build principle is defining the concept, is it a single part or a multipart design. With multi-functionality was meant that is it possible to integrate other functions to the coupling like bracket installation or mounting for clips.

Environmental conditions are that what the coupling must with stand. Corrosion is important because it reduces the strength of the coupling. Evidently a surface protection must be applied on material. The electronic bonding has to be taken into account and the fact that the coupling is going to be attached to a CFRP shell. Because there is a high possibility of a lightning strike its vital to ensure electrical bonding. The material and the surface protection choice have an influence on the couplings fire worthiness and therefore only some materials are allowed.

The manufacturing category has the aspects that have to be taken into account when the coupling is mounted to the shell. Some of the requirements are to be thought at a later stage. Tooling costs are a part of the cost of manufacturing which are reoccurring costs. The communality of the coupling concepts is that it´s designed for the A350-1000 project but with optimization it can be used for the complete aircraft family. The assembly sequence were the coupling of the two stringers is done is that at a shell level to reduce the time at the final assembly line. As a joining principle there are many ways to couple the three parts together stringers and skin and the coupling. Because the parts that are coupled are manufactured with CFRP processes they have tolerances and the coupling must be able to balance out the tolerances.

Function requirements are the functions that the coupling has to have. Because of lower shell is a liquid retention area the drainage requirement must be ensured. The coupling is a part of primary structure and the secondary structure will adapt to the primary structures design. The repair ability and inspect ability has to be met to make sure that the coupling can be installed to the aircraft. When only the allowed materials are used recyclability is met.

The requirements have to be set into order what is the most important and what is the least important requirement. For this task the method of survey report was chosen. In the survey there were three options per every requirement ´´must´´, ´´good´´ and ´´may´´. They describe how essential that requirement is in the definition and in the development of the coupling. ´´Must´´ is a requirement that has to be kept in mind and they have to be met in the end. ´´Good´´ describes a requirement that shall be fulfilled but not necessary. ´´May´´ is the category that can be taken into account but is unnecessary for the requirement list. These topics, which have seen was developed in brainstorming workshops. The results of the survey are shown in the Table 4: Survey results about which categories the requirements are and the results of the survey are used when the requirements are inputted in the value grid. There was some scattering in the results. The most and less important requirements can be seen from the results really easily. In the table must 7- means that the requirements got more than 7 ´´must´´ votes and same can be applied to the other categories.

Table 4: Survey results about which categories the requirements are

Must 7-	Must 5 - 6	Must	Good 5-	Good	May
Carry Load	Fatigue	Crash Worthiness	Multi Functions	Drainage	Recycling
Load Cases	Temperature Range	Overlapping	Thermal Expansion	Assembly sequence	
RF Bigger 1.0	Inspectability	In-line / Un-aligned	Couple Delta Height	Installation time	
Stability Stiffness	Repairability	Max Dis-Allignment	Butt-strap Delta height		
Max dimensions	Tolerancing	Fire Worthiness	Clip Assembly		
Weight	Corrosion	Material	Build principle		
Cost	Surface protection	Harmless to other parts			
	Electric bonding	Pressure range			
	Lightning Strike	Joining principle			
		Communality			

To assess the requirements in another way it is possible to create a value grid and place the requirements into it. This makes it easier to realize which requirements are more valuable. The value grid is based on the categories that have been used for sorting the requirements in. By setting a master value to every category and setting the requirements in order within the category. Table 5: Requirement value grid is illustrating the values that the requirements got from this value grid and on the top and on the side the value grid values are shown. The value comes from multiplying the master value with the place value and dividing it by the total of the value sum to get a percentages value. The requirements that are two in the same place are taken into account when the sum calculations were made as two values and not as one as shown on the table.

Table 5: Requirement value grid

Master Value Importance to the coupling Setting

Place Value	30	25	20	15	10
	Stress	Design/geometry	Product	Manufacturing	External circumstances
45	RF Bigger 1.0	Max dimensions	Weight Cost		Corrosion Surface protection
	10,63	8,86	7,09		3,54
25	Carry Load Load Cases	In-line / Un-aligned Max Dis-Allignment	Material	Installation time	Electric bonding Lightning Strike
	5,91	4,92	3,94	2,95	1,97
13	Stability Stiffness	Overlapping Drainage		Joining principle Tolerancing	Crash Worthiness Fire Worthiness
	3,07	2,56		1,54	1,02
7	Fatigue	Couple Delta Height	Temperature Range	Communality	
	1,65	1,38	1,10	0,83	
5	Thermal Expansion	Butt-strap Delta height Clip Assembly			
	1,18	0,98			
3		Inspectability Repairability			
		0,59			
2	Multi Functions Build principle	Harmless to other parts	Recycling	Assembly sequence	Pressure range
	0,47	0,39	0,31	0,24	0,16

From the different analysis of the requirements it's easy to pick the requirements that are the most essentials and when comparing the three category analysis and this value analysis there are more not so driving requirements in the value analysis. The most driving requirements were nearly the same and the middle value requirements are set to a more definitive order.

The requirement list has been defined and it's going to be used in the assessment of the concept at the analysis phase in chapter 6.3.1. The requirements have a high difference in their values due to the functions of the coupling and what are the most important functions and which ones are the least important. The results show that the design is mainly driven by stress factors and geometrical constraints.

5.2 Function Definition and Development

The main function is defined so that the sub-functions can be researched. They are the basis for searching solution to task at hand. This also gives more overview about the problem that is at hand because in this stage every function of the coupling is examined to clarify what it has to do.

The main function of the coupling concepts is to couple two stringers with various geometries and to smooth the force fluxes as much possible with the constraints that the environment produces to the coupling. The main function can be broken down into three sub-functions. The main sub-functions are nearly all the same but there are differences. All of the main sub-functions are relative to stress functions of the coupling concepts. The main sub-functions are:

- Transfer loads from the skin to the coupling and the back to the skin
- To make the joint withstand the loads that accrues at the joint environment
- Ensure the stiffness is near to a constant at the joint area

To define and develop the functions a structural box was created. This box defines the functions at a basic level like physical or chemical. It is the basis for the steps to come like the morphological box. Creation of the box helps to realize what the coupling concepts must do and what they have to with transfer. The parts that are affecting the coupling are put into the box. The basic level aspects that are coming and going out of the coupling are taken into detailed focus. Table 6: Structural box is a structural box for the coupling concepts.

Table 6: Structural box

Omega-Stringer	Coupling			T-Stringer
Axial Force	Pick up	Transfer	Release	Axial Force
Shear Force / Torsion	Pick up	Transfer	Release	Shear Force / Torsion
Bending	Pick up	Transfer	Release	Bending
Y-Position 1	Compensate			Y-Position 2
Stiffness 1	Compensate			Stiffness 2
Secondary Bending	Compensate			Secondary Bending
	Compensate Build Tolerance			
	Skin			

5.3 Solution Principles

The stage three in the VDI 2221 is to define solution principles to the sub-functions that have been researched in the chapter 5.2. The solutions are first created on a level that everything is analyzed in physical, chemical and on other effect levels. Principle solutions level is not needed in many of the cases that the sub-functions cover in this problem that we are developing a solution for. There is an example of principle level solutions in the coupling method section. The aircraft environment restricts a lot of the possible solutions because they haven't been certified for aircraft use. (VDI 1987)

For the solution a morphological box tree structure was created and then a brainstorming workshop was held to create solutions to the threes cases. A defined function tree is shown it the Table 7: Design function. The tree is very substantial and covering. The morphological box is a simple way of making concept designs with lots of variables and selections that have to be made. Using this approach gives a great overview about the choices that have to be made. The solutions to the threes topics were categorized in to go and no go scenarios and also weight and cost were evaluated in some cases. The solutions are not researched at the level that the VDI guideline suggests they should be created because the aircraft surrounding created some constraints to the options and the simplicity of the problem that is under development.

Table 7: Design function

Function
General:
Manufacturing Process for Single Part
Built Principle
Provide stiffness and strength in general:
Material
Thickness
Material Orientation
Transfer and Release load at Interfaces:
Skin to Coupling Junction / Assembly Process
Provide stiffness for enviroment forces:
Cross Section Shape
Shape in X-Direction
Level out tolerances:
Shape in X-Direction
Assembling Concepts
Smoothen Force Flux in Surroundings:
Material
Cross Section Shape
Thickness
Shape in X-Direction
Smoothen Force Flux in Coupling:
Run-out Shape
Level out tolerances in radial direction:

The manufacturing methods were researched and there were many of choices but some were a no go choices like 3d printing and laser melted because the methods are not certified to the level so that they can be used in aircrafts. Milling is one of the best options that there is because the cost of it is not so high and the weight of the design that can be done with this method is low. Bending of sheet type of material is a method that has high non-direct costs. When the molds for bending are made the costs are getting balanced after a certain amount of parts are made but the design is somewhat constrained because there are always radius at bended edges. In the bending method the weight is considered to be higher than some other methods because the geometry that can be bended has more constraints than milled ones. Casting is more costly than the other methods because traditional casting is not an option because of the high accuracy demand. Forging is highly costly because the manufacturing method is expensive. The composite manufacturing methods are nearly the same. They have some different aspects but the end result is nearly the same. Material costs are different for example the resin that is used for RTM is different than the resin used for hand lay-up. Compression molding is a feasibly solution but it is not taking all of the benefits out of the fiber construction and that means a higher weight gain than in other fiber manufacturing methods. A summary of the solution to single parts manufacturing methods is in the Table 8: Manufacturing methods where the evaluations of the methods and methods are shown.

Table 8: Manufacturing methods

	Go / No GO	Cost	Weight
Milling	Go	+	+
Bending	Go	+	-
Casting	Go	+	-
Forging	Go	-	-
Hand lay-up	Go	0	+
RTM	Go	0	+
Infusion	Go	0	+
Compression Molding	Go	+	-
3D printing	No Go	No Go	No Go
Laser melting	No Go	No Go	No Go
[Cost] - = High Cost 0 = Neutral + = Cheap [Weight] - = High weight Gain + = Low weight Gain			

Built principle describes how the coupling itself is assembled and at which point is it integrated to the aircraft. A single part has the best concept of having one part and the cost of manufacturing a single part is not so high although it’s highly complex part. Pre-assembly configuration is also not expensive but the weight is higher because of over-lapping parts. Final assembly is a highly costly choice because it will increase the lead time of the final assembly. Also the weight impact of the part that is built at the final assembly has lower weight because of the building tolerances can be taken into account. There were not so many options for a build principle because of the topic is defined in detail. Single and preassembly and final assembly covers basically all the principles that there is for this concept. The summary of the build principles is in Table 9: Build principle.

Table 9: Build principle

	Go / No GO	Cost	Weight
Integral	Go	+	+
Differential Preassembly	Go	+	-
Differential Finalassembly	Go	-	-
[Cost] - = High Cost + = Cheap [Weight] - = High weight Gain + = Low weight			

To provide stiffness for the coupling there are two selections to be made, material and material orientation if composites are used and if metals are used the material thickness provides stiffness. The material can be pre-selected and then the other selections have to be made before DFEM calculations. The materials are evaluated with weight and stiffness and with the basic evaluation methods. CFRP and CFRT have the same capabilities it this comparison. There are some differences specially when there is a large force that needs to be carried. All of the high end materials are highly expensive because they are aircraft certified. The aluminiums are a little bit less expensive than the rest but it has a worse weight to material properties ratio. Glare is not a good choice because the stiffness is not the best. Titanium is one of the best options. Magnesium is an interesting solution but the stiffness is not so good but the density of the material is really optimum for aircraft use. Ceramics have a damage tolerance factor which is not suitable for this kind of use. The hybrid and sandwich materials were a no go because their complexity. The summary and the evaluation of different materials solutions are in the Table 10: Material solutions.

Table 10: Material solutions

	Go / No Go	Cost	Weight / Stiffness
CFRP	Go	-	++
CFRT	Go	-	++
Glare	Go	-	+
Aramid	Go	-	-
Aluminium lithium	Go	+	--
Aluminium	Go	+	--
Titanium	Go	-	++
Magnesium	Go	-	+
Polymers	Go	-	+
Ceramic	No Go	No Go	--
Hybrid	No Go	No Go	--
Sandwich	No Go	No Go	--
Cost - = High Cost 0 = Neutral + = Cheap Weight - = High weight Gain 0= Neutral + = Low weight [Weight Stiffeness] -- = High weight and low Stiffeness ++ = low weight and high stiffeness			

The skin carries the loads when the stringers are cut because of cutout due to different items that are attached to the skin. The force has to be transferred from the skin to the interface of the coupling. The skin and the coupling have to be coupled in a way than it can withhold the loads that are applied to it. There are many solutions to this task for example it can be riveted. Riveting is expensive if NRC are considered but it has a low weight impact to the concept. Using a bonding method where extra material is set in has a high cost but the weight is not affected much because it can be taken into account when designing the coupling concept. Extra material can be CFRP for instance. Cobonding has a very low impact on the weight gain but it's highly expensive and really hard of a process to get it properly working. Gluing where an adhesive would be applied to ensure the skin and coupling joint is expensive but with that method the coupling would not have so many high stress spots as the riveted part would have. Welding is a no go because the shell is made out of CFRP and welding for composite parts isn´t yet certified for aircraft used.

At a primal level magnetic and electrical joining method is also a no go because of the materials that are to be coupled and also that they are not suitable for aircraft use because of long lifecycle requirements because of the conditions within the aircraft. The same goes for friction because the load that it has to transfer is a high one. Adhesion is a solution at a primal level and it's commonly use in the aircraft but not in primary structure. Positive locking where the shapes of the two items that are coupled are restricting the movement of the coupling is a no go because complexity of the design in this case. The summary is illustrated in the Table 11: Coupling solution

Table 11: Coupling solution

	Go / No Go	Cost	Weight
Possible Solutions			
Riveting	Go	+	-
Bonding Extramaterial	Go	-	0
Cobonding	Go	-	-
Gluing	Go	-	0
Welding	No Go	No Go	No Go
Physiological options			
Adhesion	Go	+	-
Friction	Go	-	-
Magnetic	No Go	No Go	No Go
Electrical	No Go	No Go	No Go
Positive Locking	No Go	No Go	No Go
Cost - = High Cost 0 = Neutral + = Cheap Weight - = High weight Gain 0= Neutral + = Low weight			

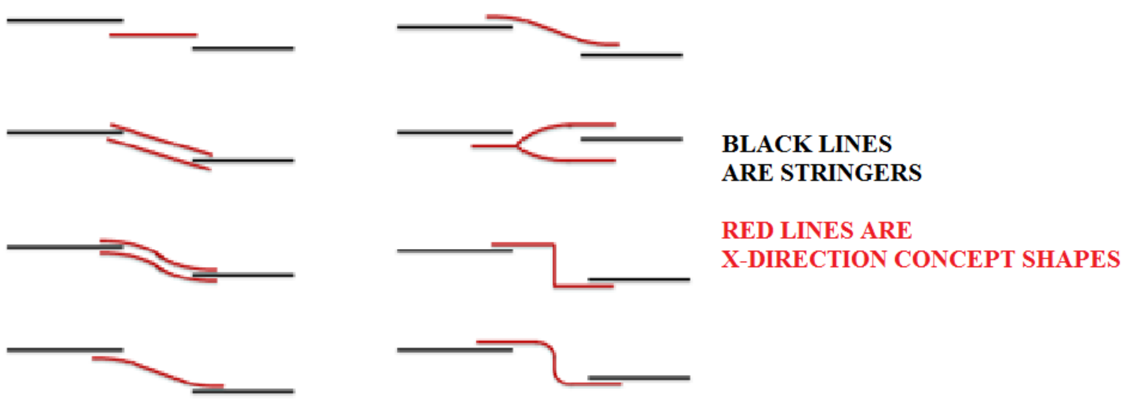
For the function to provide stiffness for bending and torsion cases and carry the loads that are introduced to the coupling we design possible cross sections. For the cross sections we went throw already realized cross sections like L, U, C and many more. There was only one cross section that was a no go and that was a hybrid shape. The hybrid shape was a combination of two cross section shapes. This was a no go for the reason that we wanted to have a simple design and a design that is manufacturing friendly. For the cost evaluation it was thought about how it can be made with different manufacturing methods and how costly every method would be. If everything would be made with milling with a multi axis mill it would be highly expensive but some of the cross sections would be more expensive than others. For example manufacturing an L is a lot cheaper than manufacturing a W concept because the milling paths are simpler for simple parts. In the Table 12: Cross section proposals are the shapes that were designed. The second moment of areas where calculated by having the same cross section area for every solution concept. When the cross section areas are the same the solutions can be compared and evaluated. Some of the shapes had a very low inertia values and some had fairly high inertia values.

Solution opportunities are compared so that the areas of the cross section are nearly the same and then the inertia is measured. L shape is used often and it’s cheap to manufacture because of the simple shape. U and C is nearly the same because they are the same but just rotated. They are easy to manufacture and they are highly strong and the shape is used in very high loaded area. Z Shape is used in not only the frames but also in panel brackets and it has good weight stiffness ratio. Mouse hole for T is a description for a geometry that is a square with a radius at the top of the square. Examples of the cross sections are in the Appendix 1: Cross Section Profile Options

Table 12: Cross section proposals

Shape	Go / No Go	Cost	IozA	IoyA
L	Go	+	++	++
U	Go	+	++	+
C	Go	+	0	++
Z	Go	+	+	++
T	Go	-	+	-
W	Go	-	0	0
O	Go	-	-	+
Ω	Go	+	+	+
Multiplex T	Go	-	0	-
Plate	Go	+	--	--
Mouse Hole For T	Go	+	++	++
I	Go	-	-	0
Multiplex Y	Go	-	--	--
Changing Shapes	Go	-		
Assembly Shapes	Go	-		
Hybrid Shapes	No Go	No Go		
More Complex Shapes	Go	-		
Cost - = High Cost 0 = Neutral + = Cheap Weight - = High weight Gain 0= Neutral + = Low weight [Second moment of area] -- = low i Value ++ = High i value				

The longitudinal directional shape is important when the stiffness of the coupling comes in to question. Because the misalignment of the stringers is known it was easy thing to compensate the misalignment. The coupling can be attached at the stringer feet from the same side in some cases and in others it's smarter to connect the opposite sides of the stringer feet depending on the misalignment size. The most simple solutions would be a straight bar in the middle of the stringer change. Also having a bar that is angled to compensate the misalignment and transfer the loads smoothly for the one stringer to the other one. The possibility of attaching the both feet of the stringers is a good choice because of high load at the coupling. When connecting the both feet it's possible to use angle bars or use two large radius circles connected in the middle as tangents or use any mathematical line to connect the two stringer feet. When we had a workshop about to possible solutions we also thought that maybe it's possibly to connect one foot to two and for this we come up with a Y like concept that connects the T-stringers one foot to Omega-stringers feet. Solution to couple the opposite sides of the stringers came up and this could be a possibility if the misalignment would be large. The Picture 19: X- direction shape has the principles of the solutions that came up it the brainstorming workshops.



Picture 19: X- direction shape

Building tolerances from machining and curing processes of the surrounding parts have to be compensated by the coupling. Shims are the most used tolerance correcting tool that is used in the aircraft industry. There are liquid and solid shims and the main difference is that when the gap that has to be shimmed is large solid shims are used but when the gap is small the liquids ones are used. Flexible part could be a possibility but it's a no go because it can't with hold the loads that come to the coupling at the designed location. Manual adjustment of the coupling to get it to tolerances can be done if an metallic concept is used but there are some things that have to be taken into account if this is done like corrosion protection and the increase in the lead time. Multipart overlapping is a heavy and an expensive solution. Simultaneously installation of parts in this case means cobonding the shell, stringers and coupling all at the same time. This can be done with CFRP concepts but its highly complex operation and the cost of this is very high but the weight of this solution is optimum in this case. Not taking the tolerances into account is an option but this may cause unwanted stresses to the structure and this has to be check if used in the concepts. The Table 13: Build tolerance has the solutions that were design for this tolerance correction case and the summary of the solutions and the evaluation of the concepts.

Table 13: Build tolerance

	Go / No Go	Cost	Weight
Shims	Go	-	-
Flexible Part	no go	+	0
Manual Adjustment	Go	0	0
Multipart overlaping	Go	-	-
Simultaneously installation of parts	Go	-	+
Leaving openings	Go	+	+
Cost - = High Cost 0 = Neutral + = Cheap Weight - = High weight Gain 0= Neutral + = Low weight			

To ensure that force flux is as smooth as possible the coupling has to have a run out and a run in. The run in's and out's function is to transfer the load from the skin to the web and the back to the skin. There are many types of run outs. The most common ones are angled and elliptical shapes. The angled ones are commonly used with T-stringers and the elliptical ones are commonly used for Omega-stringers. A two stage angle cut is used also for the t stringers. Also the solution on having any kind of mathematically defined shape came up but this would mean that it should be researched that isn't a good solution because the validation costs a lot of money and takes time. The summary of the solutions and the evaluation of the concepts are shown Table 14: Run out shape options.

Table 14: Run out shape options

	Go / No Go	Cost
Streight Cut	No Go	-
Angle Cut	Go	+
Two Stage Angle Cut	Go	-
Omega Type Epiliptical	Go	-
Combination to Two cuts	Go	+
Foot only Area	Go	-
Any Mathematical Description	Go	0
Cost - = High Cost 0 = Neutral + = Cheap		

There are tolerances that appear in the radial direction and they have to level out in some way. The most used solution to level out the tolerances is to use shims. Milled contour can also be a possibility but it's costly and weight gain is larger. Padding the single part is the same as a milled contour with a CFRP part where cost is neutral because they can be taken into account in the design. Manufacturing the couplings after the shell has been manufactured and then measured is a good idea but this solution is highly costly because it will increase the lead time of the manufacturing process of the shell. The solutions are evaluated and shown on the Table 15: Tolerance in radial direction.

Table 15: Tolerance in radial direction

	Go / No Go	Cost	Weight
Shimming	Go	-	-
Juggled / Milled contour	Go	+	+
Padings in single parts	Go	0	+
Manual Adjustment (Grinding)	Go	0	0
Measuring tolerances > Manufacturing parts Accordingly	Go	-	+
Overlapping Parts	Go	-	-
Simutaneously installed (i.e. Cobonding)	Go	+	+
Cost - = High Cost 0 = Neutral + = Cheap Weight - = High weight Gain 0= Neutral + = Low weight			

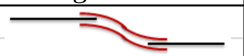
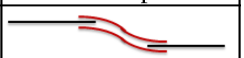
To have a smooth force flux into the surroundings the following solution groups material, cross section shape, X directional shape and thickness have an effect of the case. The surroundings are highly complex because of cut outs and double curved area the DFEM calculations are the only way of making sure that the coupling concepts work within the desired range.

5.4 Realizable Solution

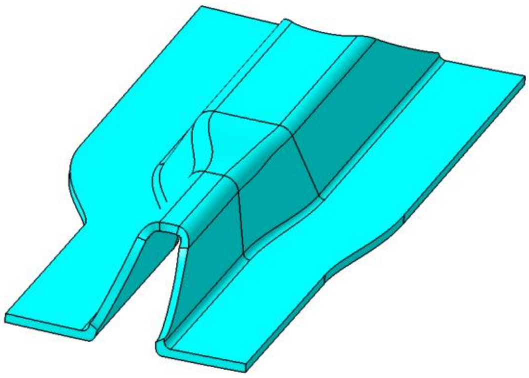
The stage four of the VDI 2221 guideline is the stage where the principle solutions are divided to realizable concept solutions and this is done because it saves time on the development of the solutions. The development of the solutions is time intensive and therefore the solutions have to be selected carefully and made certain that the solutions are compatible. (VDI 1987)

In the attached files there is a collection of all of the solutions within one table. From the table it's easy to select the best solutions and make the combinations of the selected solutions. Three concepts are taken combined from the morphological box and embodied in to CATIA models as simple versions. The three concepts were selected by putting the solutions in order by their feasibility and best properties that have been evaluated in the chapters 5.3 tables. The tables are collected into a morphological box which is in the Appendix 2: Morphological Box of the Concept Solutions. When combining the concepts it was important that the combined solutions are combinable. The concepts are described in the Table 16: Concept definition.

Table 16: Concept definition

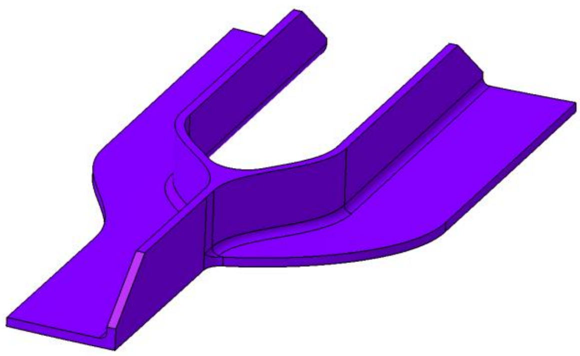
Concept title	**Concept 1**	**Concept 2**	**Concept 3**
Manufacturing process	Milled	Milled	Bended
Build principle	Single Part	Single Part	Mutli Part
Material	Titanium	Magnesium	CFRP
Coupling method	Riveting	Riveting	Cluing
Cross section shape	Omega/mousehole	L Shape	L Shape
Longitutional shape			
Compensation of tolerances	Shimming		
Runout shape	Elliptical Run Out	Angled Run Out	
Radial tolerance compensation	Milled Contour	Milled contour	Leave openings

The concept one is design so that it would be milled from a block or from a casted pre part of titanium and it would be riveted on the shell true the stringer feet and skin. It can be shimmed into its correct spot but it’s milled so that the biggest gaps are filled by the coupling itself. The coupling is lying on top of the stringers and the feet can be attached smoothly because the coupling has taken the thicknesses of the stringer feet in to consideration. The Picture 20: Concept one is illustration of the coupling. The foot of the coupling takes also into consideration the two different widths of the stringer feet.



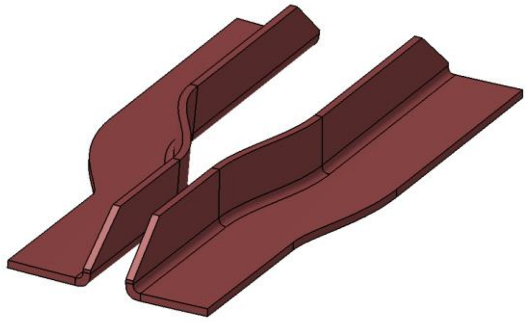
Picture 20: Concept one

The concept two is a milled part that is made from magnesium as a single part that is riveted on the shell. A milled contour is easy to make come true because the part is already going to be milled from a block. The Y concept in the x direction can make some interesting affect because it has an unsymmetrical riveting path but this was not researched due to the time constraints. The concept principal is illustrated the Picture 21: Concept two.



Picture 21: Concept two

The concept three is designed so that it will be bended and made out of CFRP and it can be attached to the shell by gluing. The concept is a multipart design with two separate parts. Because the cross section shape is an L shape an angled shape run out is used. The concept defines that the gaps left open and this makes the mold a little less complicated. The Picture 22: Concept three embodies the concept and with the concept there is the shell that the concept attaches to.



Picture 22: Concept three

5.5 The VDI Guidelines Adaption

Key module development stage is adapted in the realizable concept and in the optimization loops of the concepts where different materials are adapted. The detailed design covers the key module section of the guideline but because the task is too time-consuming it was not done.

The definitive layout stage of the guideline is not adapted due to the fact that the design which was created can be used for concept comparison but not for more and because of that the drawings and parts list and assembly data cannot by created from this concept design.

Product documentation stage is adapted in a way that the development of the concepts is documented in this thesis. All of the analysis and design aspects are documented in the way that is covering the bases for the selections that were made. Because of the nature of the task the adaption was made in this way.

6 ANALYSIS AND CALCULATIONS

6.1 Stress Analysis by Hand

6.1.1 Hand Calculation General

Deleted for confidentiality reasons.

6.1.2 Principles of Hand Calculations

Deleted for confidentiality reasons.

6.1.3 Assumptions

Deleted for confidentiality reasons.

6.1.4 Fastener Amount

Deleted for confidentiality reasons.

6.1.5 Buckling (Euler)

Deleted for confidentiality reasons.

6.1.6 Compression

Deleted for confidentiality reasons.

6.1.7 Sizing Loops

Deleted for confidentiality reasons.

6.1.8 Best concept geometrical and material

Deleted for confidentiality reasons.

6.2 Computer Aided Stress Calculations

6.2.1 GFEM and DFEM

Deleted for confidentiality reasons.

6.2.2 Environment of the DFEM

Deleted for confidentiality reasons.

6.2.3 Load Introduction

Deleted for confidentiality reasons.

6.2.4 Concept Analysis

6.2.4.1. Concept One

Deleted for confidentiality reasons.

6.2.4.1.1. Assumptions

Deleted for confidentiality reasons.

6.2.4.1.2. Material Strength

Deleted for confidentiality reasons.

6.2.4.1.3. Compression Buckling

Deleted for confidentiality reasons.

6.2.4.1.4. Shear Buckling

Deleted for confidentiality reasons.

6.2.4.1.5. Combined Compression and Shear Buckling

Deleted for confidentiality reasons.

6.2.4.1.6. Fastener Metallic

Deleted for confidentiality reasons.

6.2.4.1.7. Fastener Composites (Filled Hole Analysis)

Deleted for confidentiality reasons.

6.2.4.1.8. Displacement of the Concept

Deleted for confidentiality reasons.

6.2.4.2. Concept Three

Deleted for confidentiality reasons.

6.2.4.2.1. Assumptions

Deleted for confidentiality reasons.

6.2.4.2.2. Damage Tolerance Edge Impact

Deleted for confidentiality reasons.

6.2.4.2.3. Compression Buckling

Deleted for confidentiality reasons.

6.2.4.2.4. Shear Buckling

Deleted for confidentiality reasons.

6.2.4.2.1. Combined Compression and Shear Buckling

Deleted for confidentiality reasons.

6.2.4.2.2. Fastener Composites (Filled Hole Analysis)

Deleted for confidentiality reasons.

6.2.4.2.3. Displacement of the Concept

Deleted for confidentiality reasons.

6.2.5 Problems That Occurred When Creation the Model

Deleted for confidentiality reasons.

6.3 Assessment Analysis

6.3.1 Concept Design Analysis

The concepts are analyzed using the requirements that were introduced in the Table 5: Requirement value grid also the value grid factors are taken into account in the calculations of the results. Some of the requirements are met by all of the concepts because they have the same solution of meeting the requirement and therefore they are not cases that are to be analyzed. The analysis survey was held to analyze the concepts and their parameters and the requirements that were analyzed are in the Table 17: Requirement fulfillment analysis.

Table 17: Requirement fulfillment analysis

	Concept 1	Concept 3		Concept 2	Value Factor
	Riveted	Glued	Riveted	Riveted	(Table 5)
Stress					
RF greater then one / Weight	3	3	3	1	10,630
Fatique	2	3	3	1	1,650
Thermal expantion	2	3	3	1	1,180
Design					
Max dimension	2	3	3	3	8,860
Max mis-alingment	2	1	1	3	4,920
Inspectability	3	1	3	3	0,590
Drainage	3	3	3	1	2,560
Repairability	3	1	3	3	0,590
Product					
Cost	2	3	3	3	7,090
Recycling	3	1	1	3	0,470
Manufacturing					
Installation time	2	3	2	1	2,950
Tolerancing	3	2	2	3	1,540
External circumstances					
Corrosion / Surface protection	3	3	3	1	3,540
Electric bonding / lightning strike	1	3	3	1	1,970
Value as evaluated	2,429	2,357	2,571	2,000	3,467
Percentage of fulfillment of the requirements	0,789933	0,899	0,8951	0,663782	%

The results show that all of the requirements are filled but with different values for example the max misalignment for concept three is the worst due to the material draping and the misalignment of the concept one is limited by the material and the geometry will get inconsistent shapes at large distances but the concept two can be created in a way that can cover a large misalignment. The results of the analysis show that concept three and concept one should be researched more and also optimized to the requirements of the concepts.

6.3.2 Stress Analysis

Deleted for confidentiality reasons.

6.3.3 Solution Optimization

Deleted for confidentiality reasons.

7 CONCLUSIONS

The thesis contains a lot of aspects that have to be taken into consideration from design and stress point of view. The use of several programs is needed to get the results that are needed to evaluate and analyze the concepts and to develop. Because of the thesis has been created in Airbus environment Airbus tools have been used and this is the reason for the many programs that have been used in the thesis.

The application of the VDI 2221 gave the thesis systematic steps to develop the concepts. The guideline was adapted to the task and this worked because the task was to only develop the concepts to a level were the concepts can be stress analyzed and compared. The detailed design that could be a way forward could be the final stages of the guideline. The concepts that were realized in 3D models were selected from various solutions to cover the various requirements that the concept has to fulfill.

The concepts that were designed work and they can be applied to the shell of a 4 Omega- stringer concept. The designed model of the concepts that were done in CATIA is not useable in an aircraft but the concept can be analyzed with the model and the basic idea of the concept is illustrated in that model. The model that was created needs a detailed design where all small details have to be taken into account for example the duck feet of the stringers and the stringer run out and the foots thickness differences.

Hand calculations were performed with many assumptions and they only take the material properties and a simple geometry into consideration but from the hand calculations some assumptions can be made. The detailed computer aided calculations were necessary because of the materials used and that geometry being so complex.

The stress analysis was done with the help of different programs which are HYPERMESH and NASTRAN and PATRAN and ISAMI and EXCEL. The large number of programs meant that it took a long time to get familiar with the programs. Also the creation of the template for the calculations and the selection of the methods of calculation took a long time also the selection of the aspect that are calculated was a time-consuming and difficult task. The environment creation was the most time-consuming task of the stress analysis because the meshing and the connection creation took along time because of the complexity of the environment.

RF values from pre-selected calculations show that the same weight solutions are highly different in RF value and this comes from the geometrical and from the material differences. The RF value shows that the CFRP material is better than titanium in strength comparison and from that also in weight. Although the CFRP is more costly and harder to design than titanium version it is worth the effort because of the benefit of the material.

A low level optimization was done for concept one and three. The low level optimization was done in a way where concept one with titanium was optimized and also a CFRP version of the concept was calculated to compare the concept one and three with the same material. The optimization shows that the titanium version is high weight solution in comparison to the CFRP version of the concept one. The optimization also shows that the concept three is better than concept one if same material is applied. This was a surprise because in the hand calculations the concept one was the best solution in the hand calculations.

The thesis had its own difficult section of it but they were overcome with the assistance of colleges and by researching the possibly solutions to the difficult sections. Making the thesis was demanding and at some point very challenging but it was also very teaching and rewarding when the difficult sections were overcame. The results show that the concepts can be used to couple the two stringers but the effect on the surrounding and the entire environment has to be researched with using more than one concept.

8 WAY FORWARD

The way forward can be started in many ways but the most important task that has to be done is to change the GFEMs configuration from a 5 T-stinger to 4 Omega-stringer version in the lower shell. This has to be done if the 4 stringer concept is going to be used. The definition and the detailed design of the stringers have to be done keeping the stress point of view in mind. Also the skin and the clips have to be defined to meet the 4 stringer configuration that a DFEM can be created.

The coupling concepts can be still optimized but before the DFEM were the inputs are taken from for the optimization has to be validated and this means that the DFEM has to be compared to the GFEM that they behave in the same way. The calculations were made only for one load case but all of the load cases have to be taken into account if the coupling concept is to be verified that it can with stand all of the loads that are occurring to the concept. The fatigue case also has to be calculated and analyzed. The effect on the surroundings of the coupling has to be checked because of the cut out in the near surroundings. Usually the cut outs are defining the design because the cut outs shouldn't have too large stresses to carry. Also the skin has to be checked if the surrounding of the change has to be padded up or can it carry the loads with the current layup at the location.

The concepts can be optimized in many ways. The best concept is the one with the lowest weight and the lowest cost. To develop the best the material selection has to be the optimum and the geometry has to be optimum as well keeping in mind the amount of work put into it. The best run out type also has to be design to get the best possible concept. The manufacturability of the concepts has to be analyzed especially if CFRP is used as material because it has many constraints like for instance draping angle and layup configuration. Draping means if the CFRP can fold to the shape and will the layers keep their desired fiber directions or are they ten percent off in some locations. The fasteners also can be optimized when the concepts are optimized to get the most optimized solution. If the concept is made out of CFRP the layup and the layups layers geometry can be optimized as well to get the most optimized concept but this is already very fine tuning of the concepts.

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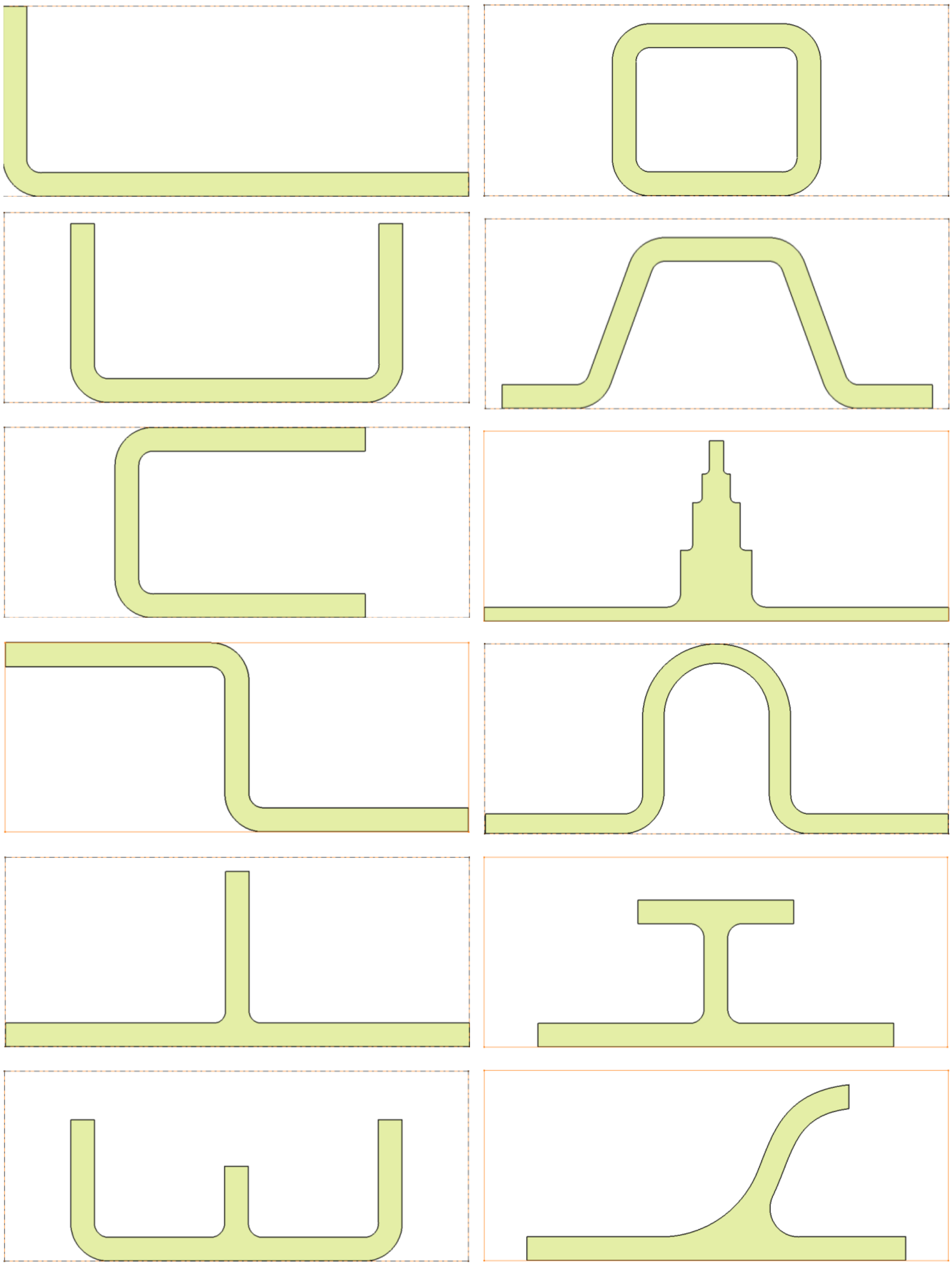
ATTACHED FILE

Appendix 1: Cross Section Profile Options

Cross Section Collection which were designed with the same weight and then the inertias were compared.



Appendix 2: Morphological Box of the Concept Solutions

Function	Solution 1	Solution 2	Solution 3	Solution 4	Solution 5	Solution 6	Solution 7	Solution 8	Solution 9	Solution 10	Solution 11	Solution 12
General:												
Manufacturing Process for Single Part	Milling	Bending	Casting	Forging	Handlay up	RTM	Infusion	Compression molding	3D Printing	Laser Melting		
Built Principle	Single Part	Preassemly	Final Assembly	1...3...X								
Provide stiffness and strength in general:												
Material	CFRP	CFRT	Glare	Aramid	Aluminium lithium	AL.	Ti.	Mg.	Polymers	Ceramis	Hybrid	Sandwitch
Thickness	Depends on the design											
Material Orientation	Depends on the design											
Transfer and Release load at Interfaces:												
Skin to Coupling Junction / Assembly Process	Bonding (Extramaterial)	Riveting	Cobonding	Cluing	Welding	Magnetic	Electrical	Friction				
Provide stiffness for bending /torsion and transfer forces:												
Cross Section Shape	L	U	C	Z	T	W	O	Ω	Changing Shape	Assembly Shape	Hybrid Shapes	More Complex Shapes
Shape in X-Direction	Angled/Streight	Angled one	From two to one feet	Connection of Feet: -Feet Connected same side -Different Sides of the feet connected -Web to Feet								
Level out tolerances / build principle in circumferencial direction:												
Shape in X-Direction	Angled/Streight	Angled one	From two to one feet	Connection of Feet: -Feet Connected same side -Different Sides of the feet connected -Web to Feet								
Assembling Concepts	Shims	Flexible Part	Manual Adjustment	Mutipart Overlapping	Simultainious Installation of Parts	Leaving Openings / Gaps						
Smoothen Force Flux in Coupling												
Run-out Shape	45 Angle	30 Angle	Two stage angle	Water jet	Omega Type							
Smoothen Force Flux in Surroundings												
Material	CFRP	CFRT	Glare	Aramid	Aluminium lithium	AL.	Ti.	Mg.	Polymers	Ceramis	Hybrid	Sandwitch
Cross Section Shape	L	U	C	Z	T	W	O	Ω	Changing Shape	Assembly Shape	Hybrid Shapes	More Complex Shapes
Thickness	Depends on the design											
Shape in X-Direction	Angled/Streight	Angled one	From two to one feet	Connection of Feet: -Feet Connected same side -Different Sides of the feet connected -Web to Feet								
Level out tolerances in radial direction:												